NASA Conference Publication 3319

Soil Moisture:

Report of a Workshop Held in Tiburon, California 25–27 January 1994

Edited by Ming-Ying Wei

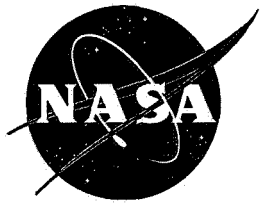
NASA Headquarters
November 1995

NASA Conference Publication 3319

Soil Moisture:

Report of a Workshop Held in Tiburon, California 25–27 January 1994

Edited by Ming-Ying Wei



NASA Headquarters
November 1995

Table of Contents

Preface 3

I. Introduction 5

II. Scientific Issues 7
- II.1. Hydrology 7
- II.2. Soil Science 11
- II.3. Ecology 14
- II.4. Meteorology 16

III. Spatial and Temporal Variability and Sampling 18

IV. Conclusions 20

V. References 22

Appendix A. List of Participants 29

Appendix B. List of Contributors 30

Appendix C. Ground-Based Measurement Techniques of Soil Moisture 31
- Gravimetric techniques 31
- Nuclear techniques 31
- Electromagnetic techniques 32
- Tensiometric techniques 33

Appendix D. Microwave Remote Sensing of Soil Moisture 34
- Passive techniques 35
- Active techniques 41

Appendix E. List of Long-term Soil Moisture Observations in the U.S. and Canada 43
1. Soil Conservation Service (SCS) soil moisture study 1979-1984 43
2. Illinois Climate Network 44
3. Nevada Soil Climate Study 44
4. SCS Global Climate Change Pilot Project 44
5. Canadian Prairie Soil Moisture Data 45

Appendix F. Soil Water and Solute Transport Equations 46

Appendix G. Glossary of Technical Terms 52

Appendix H. Additional References Regarding Soil Moisture 54
Hydrology and Remote Sensing 54
Soil Science 59
Ecology 75
Meteorology 76

Preface

Soil is a thin layer of porous material at the interface between the atmosphere and the lithosphere. The retention of moisture, or water, in the soil and the attendant runoff from naturally occurring rainfall, snowmelt, or irrigation are fundamental processes upon which civilization depends for food production, potable water, and navigable streams and waterways. Soil moisture serves a critical role in shaping the ecosystem response to the physical environment. Near-surface soil moisture controls the partitioning of available energy at the ground surface into sensible and latent heat exchange with the atmosphere, thus linking the water and energy balances through the moisture and temperature states of the soil. Adequate knowledge of the distribution and linkage of soil moisture to evaporation and transpiration is essential to predicting the reciprocal influence of land surface processes to weather and climate. Despite this importance, global measurement and analysis of soil moisture and temperature remains an outstanding scientific problem with far-reaching significance to humankind.

On January 25-27, 1994, the Office of Mission to Planet Earth of the National Aeronautics and Space Administration sponsored a workshop on soil moisture in Tiburon, California. The aim for the Workshop was to identify the scientific requirements of the atmospheric, hydrologic and ecological disciplines for soil moisture observations. These requirements would then define the conceptual framework and scientific strategy for the development and deployment of global monitoring systems of soil moisture using in situ and remote sensing techniques. Over thirty scientists representing soil science, hydrology, ecology and meteorology from U.S. and foreign academic institutions and government laboratories (Appendix A) participated in the discussion. Since widely different issues are involved in the remote sensing of snow and ice, we confined our attention to the unfrozen form of the soil moisture. This report attempts to summarize the discussions and recommend promising avenues for research to further our knowledge of soil moisture, particularly, the spacial and temporal evolution of the coupled moisture and temperature states; it is hoped that, similar to other environmental state variables, a climatology of soil moisture and temperature may eventually be defined.

This report stems primarily from the deliberations at the Workshop in Tiburon. I have benefited from the reviews and suggestions by many scientists who were not present at Tiburon; these contributors are recognized in the acknowledgment (Appendix B). Several invited papers, presented at the Workshop, will be published separately as a special issue of the *Journal of Hydrology*.

Ming-Ying Wei
Science Division
Office of Mission to Planet Earth
National Aeronautics and Space Administration

I. Introduction

Soil moisture is fundamental in several disciplines of the Earth sciences. Applications in these different disciplines have led to various strategies for estimating this variable. However, a unified approach to monitor soil moisture for multiple applications has not been defined. As a result, the National Research Council (1992) report declares: "The lack of a convincing approach to global measurement of soil moisture is a serious problem". In an attempt to chart a better course of action, the following questions were presented at the Workshop as a starting point for discussion:

1. If the water content of the upper, or surface, layer of the soil and its variation in space and time are known, what problems in soil moisture dynamics and land-atmosphere interaction can be usefully posed?
2. Given the different sampling uncertainties and other limitations of soil moisture observations (direct and inferred), how can these data best be exploited or interpreted?
3. How may the spatial and temporal variability of surface soil moisture best be characterized and modeled? How can soil moisture, evapotranspiration, and infiltration for large regions be represented? What are the effects of soil, vegetative and topographic properties, and the dynamic coupling between precipitation and evapotranspiration, on soil moisture distributions?
4. What further field experiments would help advance our knowledge of soil moisture? What are the requirements of such experiments for spatial and temporal sampling and other complementary measurements? How do we validate these requirements?

Implicit in these questions is a recognition of the different perceptions about soil moisture apparent in relevant disciplines. Indeed, Lawford (1992) observes that "to the atmospheric scientist, soil moisture is a condition which exists over a large area and affects the transfer of moisture into the atmosphere and hence may influence the production of precipitation. For the hydrologist, soil moisture on the scale of a watershed preconditions the surface and influences the amount of runoff produced by a given amount of precipitation. Soil moisture for the agriculturist is a valuable commodity which must be conserved at the farm level in order to ensure the next summer's crop will do well. Finally, the hydrogeologist looks upon soil moisture as a water source for recharging local aquifers or wells, and as a potential source for contamination when the water is transporting contaminants and biota from near-surface layers to deeper soil layers." While the four questions asked at the Workshop could themselves comprise a research agenda with significant demand on time and resources, the immediate challenge is to develop a strategy which will eventually produce and advance a coherent body of knowledge about the soil moisture behavior of the land masses.

As in the case of many geophysical variables, global measurement and interpretation of soil moisture will be best accomplished by a combination of spaceborne and ground-based techniques. In remote sensing, the development has primarily emphasized the passive and active microwave techniques due to the directly observable, large difference between the dielectric constants of wet and dry soil. Optical and infrared techniques may also provide information on soil moisture via less direct relationships between soil moisture and the thermal and vegetative conditions at the surface. Much progress has been made in technique development; however,

there is presently no well-demonstrated approach to combining remotely sensed and ground-based measurements. The subsequent scientific interpretation and modeling of soil moisture over a wide range of spatial and temporal scales also remains to be explored.

Similar to the gravimetric and several indirect methods (e.g., neutron probe, time-domain reflectometry) of measuring soil moisture in place, the soil moisture estimated from passive and active microwave remote sensing also has its unique features. For example, the sensing depth of moist soils, while varying with different electromagnetic wavelengths, is generally a few centimeters. Since it is the soil moisture profile within the root zone, extending to 1-2 meters in depth, which is of general interest to hydrologists and ecologists, it is important to determine whether the water content at depths below the upper, or surface, layer of the soil can be inferred from the upper boundary conditions. Also, remote sensing measurements are really averaged values. Given the heterogeneity of soils and the likelihood of a mixed pixel of varying soil and vegetation characteristics, it is equally important to know whether a useful spatially-aggregated soil moisture quantity can be extracted.

The definition, sampling and estimation of an aggregated soil moisture quantity is complicated by factors such as the heterogeneity of soil properties, topographic and drainage characteristics, vegetation influences and intermittent precipitation patterns. For the same reasons, the inference of soil moisture at scales smaller than the size of a satellite footprint or the area of a spatial average (i.e., the problem of disaggregation) is also a scientific challenge.

With the above aims and considerations in mind, the Workshop began with invited presentations by Ignacio Rodriguez-Iturbe, Donald R. Nielsen, Christopher B. Field and Roger A. Pielke on issues and opportunities relating to soil moisture as viewed from the disciplines of hydrology, soil science, ecology and meteorology, respectively. A review of current soil moisture monitoring in the U.S. was then given by Konstantine Georgakakos, which was followed by tutorials on active and passive microwave remote sensing by Fawwaz Ulaby and Eni Njoku, respectively. Since sampling considerations are central to any measurement program or plan, Gerald R. North (substituted by Juan B. Valdes) provided the lessons learned from the Tropical Rainfall Measuring Mission concerning this issue (North and Nakamoto, 1989). To provide a context for the state of the art in remote sensing of soil moisture, Thomas J. Jackson and Jakob van Zyl presented experimental results of the Electronically Scanned Thinned Array Radiometer (ESTAR) and the airborne synthetic aperture radar (AIRSAR), respectively, from a campaign over the Little Washita Watershed, Oklahoma, in summer 1992. The Workshop then continued with discussions in subgroups identified by disciplines, though the actual participation in each of the subgroups was interdisciplinary.

Section II in this report contains summaries of the discussions from the hydrology, soil science, ecology and meteorology subgroups. Section III considers the issues of spatial and temporal variability and the design of sampling strategies. This report concludes with Section IV. Several appendices are provided for the convenience of the non-specialist. A brief description of several ground-based measurement techniques of soil moisture is included in Appendix C. The status of passive and active microwave remote sensing of surface soil moisture is briefly discussed in Appendix D. Since there are few sets of long-term soil moisture data, a brief list of several observing sites in the U.S. and Canada are included in Appendix E. Appendix F contains a summary of soil water and solute transport equations. A glossary of technical terms is included in Appendix G. Finally, additional references which may be useful in research across disciplines are collected in Appendix H.

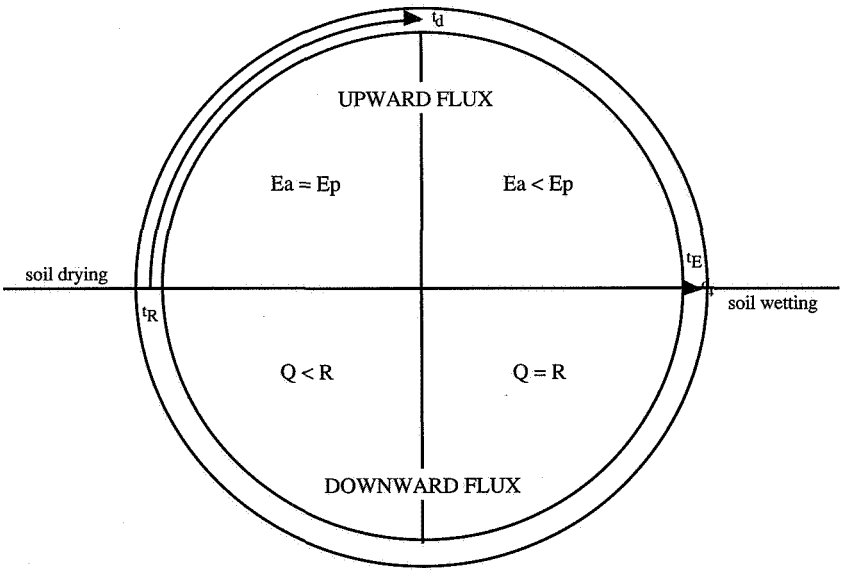
II. Scientific Issues

II.1. Hydrology

Participants: L. Band, M. Celia, J. Dooge, T. Engman, D. Entekhabi, K. Georgakakos, D. Goodrich, R. Koster, D. McLaughlin, I. Rodriguez-Iturbe, P. A. A. Troch

The highly intermittent character of precipitation, the topographic control on soil water flow, the heterogeneity of the soil, and the biotic control of moisture extraction in the root zone result in challenges for the three-dimensional study of soil moisture dynamics. The moisture state of the surface layer of the soil changes with the seasons and the characteristics of storm and interstorm periods. The coupling between the unsaturated zone and the groundwater through infiltration or exfiltration, with the frequent occurrence of preferential flow, is further related to the regional drainage network and the structures of the soils. These processes operate over a wide range of time and space scales.

The upper layer of the soil is intermittently a source and a sink for moisture (Figure 1). When the control over land-atmosphere interaction is dominated by the meteorological or climatic conditions, the soil can absorb (or yield) moisture at the rate which the overlying atmosphere provides (or demands); when infiltration-excess runoff occurs, or when the actual evapotranspiration is less than potential evaporation, the control is switched to the soil and vegetation (Kuhnel et al., 1990; Salvucci and Entekhabi, 1994).



Ep:	Potential evaporation	t_d:	time to desaturate surface
Ea:	Actual evaporation	t_E:	total duration of drying period
R:	Rainfall rate	t_p:	time to surface ponding
Q:	Infiltration rate	t_R:	total duration of rainfall period

Figure 1. Soil-atmosphere interchange of moisture during a wetting and drying cycle (from Kuhnel et al., 1990).

Traditionally, hydrologists have had to operate with limited or no information about the three dimensional distribution of soil moisture and its variation in time. Ground-based methods for observing soil moisture, such as gravimetric techniques, neutron probes, time domain reflectometry (Appendix C), are generally labor intensive. Except for selected sites of agricultural concern and certain research watersheds (Appendix E), the data necessary to characterize soil temperature and moisture profiles at the regional or continental scale are conspicuously missing. The progress of the spatially distributed and physically based water balance models introduced in the past two decades has certainly been hampered by the lack of data adequate for prognostic and diagnostic purposes.

Remote sensing of surface soil moisture at microwave frequencies (Appendix D) will no doubt contribute significantly to the investigation of soil moisture distribution and dynamics. Shown in Figure 2 (page 38) are some experimental results exhibited at the Workshop; the volumetric water content for the top 5 cm of the soil has been converted from the brightness temperature (Figure D5; page 39) as detected by the airborne Electronically Scanned Thinned Array Radiometer (ESTAR) at 1.4 GHz over the Little Washita Watershed in Oklahoma during an 8-day dry-down period (Jackson et al., 1995). The ease with which remote sensing instruments can estimate large-scale distribution of surface soil moisture is attractive; however, the difficulty lies in validating such maps and relating them to the subpixel distributions and profiles of field soil moisture existing at depths of the order of 1-2 meters within the root zone.

Estimation of water fluxes at the land surface requires soil moisture data at differing space and time resolutions, depending on the governing physical processes involved. Figure 3 gives a general picture of the characteristic spatial and temporal scales associated with some of these

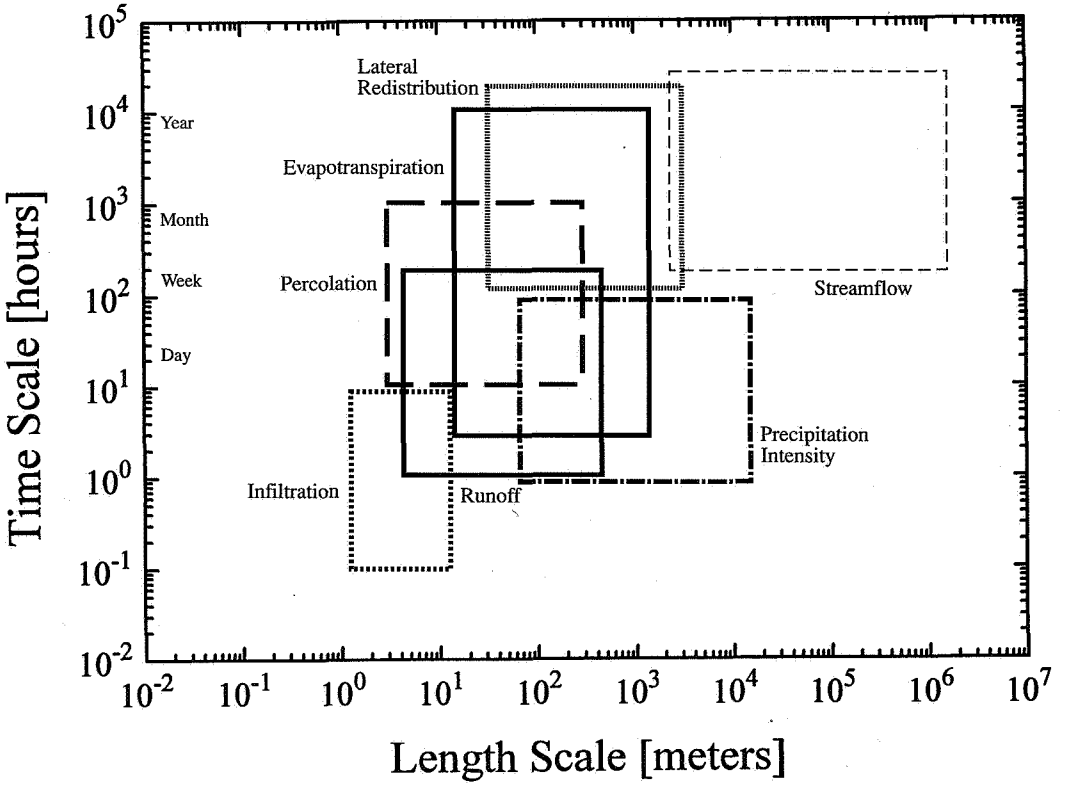


Figure 3. Illustrative range of scales of some hydrologic processes.

processes. Specific regional or local application with differing topography, spatial heterogeneity, vegetation and climate may modify the entries depicted.

By combining a one-dimensional coupled heat and moisture diffusion model for porous media and a radiative transfer model, Entekhabi et al. (1994) demonstrated the feasibility of estimating the soil moisture and temperature profiles by solving the "inverse" problem using simulated time-varying remote sensing measurements as upper boundary conditions. Such an approach, if successfully extended to large horizontal dimensions, might be designed to make optimal use of the strengths of both ground-based and remote measurements. The direct assimilation of radiances into a coupled model of radiative transfer, soil moisture and heat flux also avoids the empirical relations often invoked in the retrieval of surface soil moisture. Additional work is needed to incorporate the role of vegetation, topographic control and soil heterogeneity into such assimilation schemes. The incorporation of auxiliary information, such as streamflow, may also serve to reduce the uncertainty associated with the retrieval of soil moisture over large and complex terrains. If the experience with four-dimensional data assimilation (4DDA) in meteorology is any guidance, such methods may be an important research direction which may eventually lead to routine analyses of soil moisture and temperature. The viability of such approaches can be examined now with properly designed numerical and field experiments.

The land and atmosphere interact through the exchange of energy (e.g., radiation, sensible and latent heat) and momentum in addition to water. As the key state variable at the soil-atmosphere interface, the surface moisture state (Figure 4) determines the partitioning of surface radiative forcing into sensible and latent heat fluxes and the partitioning of precipitation into runoff and infiltration storage; additionally, the albedo and thermal emissivity of the land surface

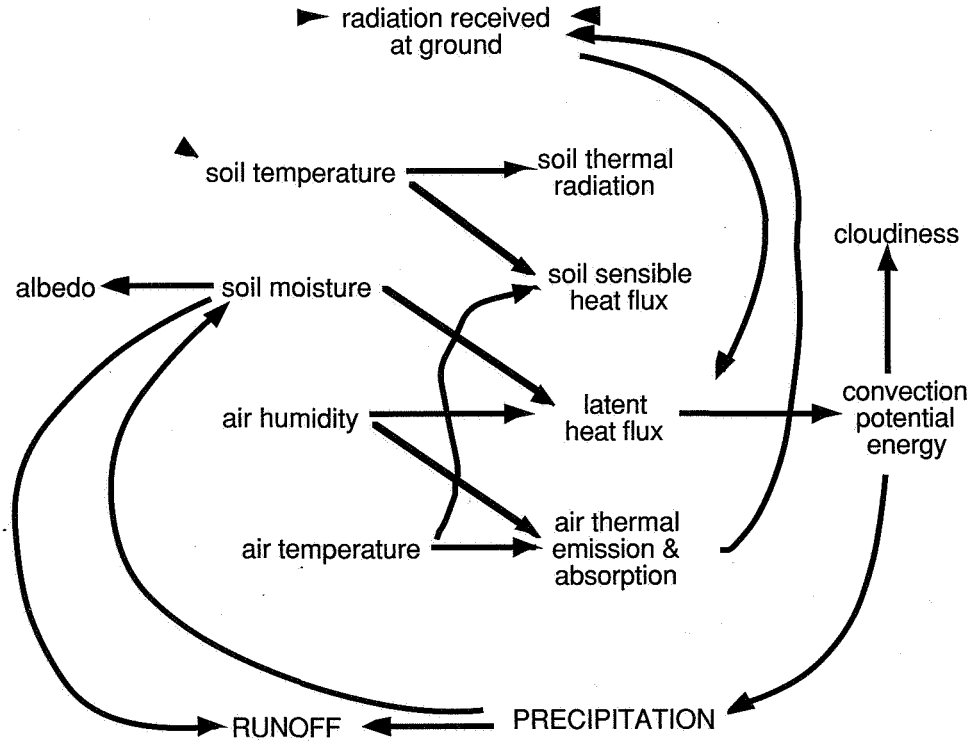


Figure 4. Conceptual diagram of the pathways through which soil moisture affects and is mutually influenced by the overlying atmosphere (from Brubaker and Entekhabi, 1994).

are dependent upon the surface soil moisture and the dissolved mineral content. Over short time scales (e.g., weather), the development of planetary boundary layer and cloudiness is dependent upon the evaporation and transpiration from the land surface, which is further discussed in Section II.4. For longer time scales, the memory associated with soil moisture and heat storage, along with the thermal inertia of the oceans, contributes to the seasonal and interannual variability of the regional and global climate.

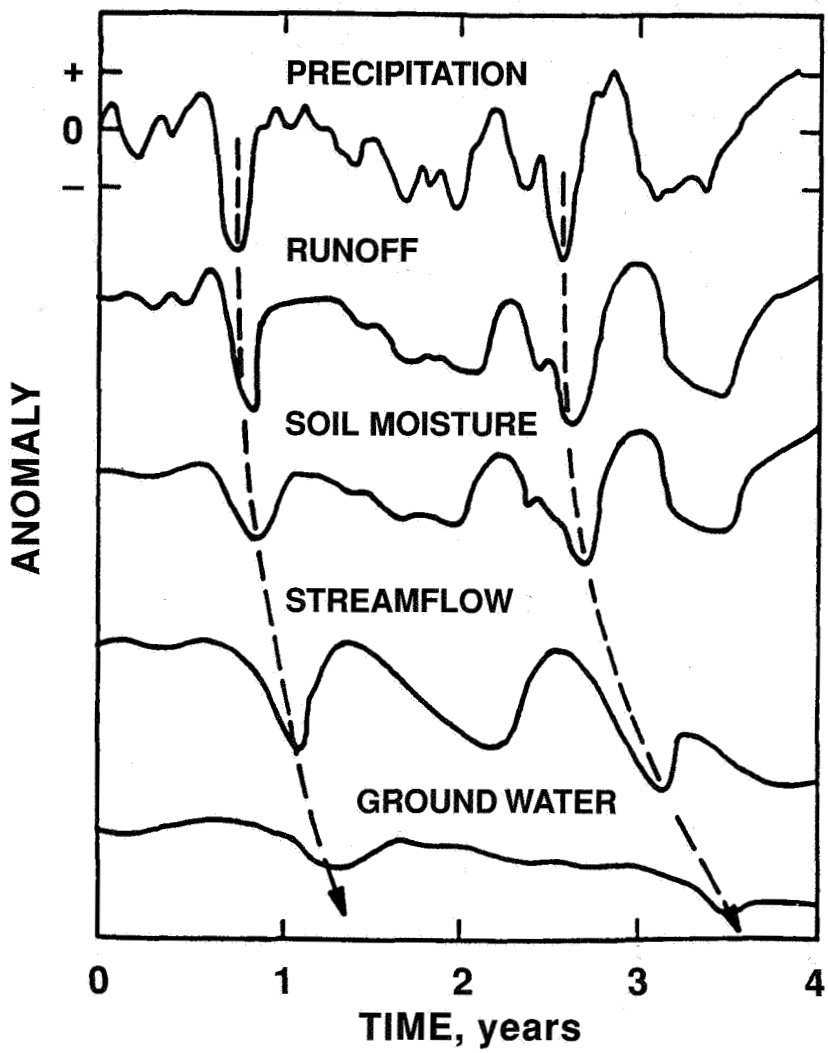


Figure 5. The propagation of precipitation anomaly through the surface branch of the hydrologic cycle (from McNab and Karl, 1989). Land-atmosphere interaction and feedback mechanisms, if fully depicted in this figure, would include the influence in the upward direction.

Depicted in Figure 5 is a schematic of the propagation of precipitation anomalies through the surface and subterranean branches of the water cycle (McNab and Karl, 1989). In contrast to the simplified characterization in this figure, in which anomalies in soil moisture and runoff are traced to anomalies in precipitation, anomalies in atmospheric phenomena due to anomalies in soil moisture is far more difficult to isolate and identify. This is partly due to the lack of routine observations of soil moisture and temperature. The great dust bowl in the U.S. (in the 1930's) and the great Mississippi flood of 1993 are just two examples which challenge our understanding of the role of soil moisture in the global water cycle and regional climate variability.

The interaction between land surface processes and weather and climate is only one among several frontier research topics discussed in *Opportunities in Hydrologic Sciences* (National Research Council, 1991). Characterization of spatial and temporal variability of soil properties and scaling of the dynamic behavior of transport are also among the emerging topics. For example, how can local observations of soil moisture, infiltration and preferential flow be translated to larger regions? What theoretical approaches and experimental methods are appropriate to aid in the identification of a model structure and spatial-temporal estimation scheme for simulating subsurface fluid flow? As deterministic models of infiltration and unsaturated soil water flow are complemented by spatially stochastic concepts, a conceptual framework defining the statistical structure of soil water properties from local to global scales is needed. More about spatial and temporal variability will be said in the context of sampling in Section III.

II.2. Soil Science

Participants: O. Baumer, K. Bristow, R. Cuenca, D. Nielsen, G. Uehara, M. van Genuchten, J. Wagenet

A soil develops at the landscape scale under mutually interacting climatic, biotic, topographic, geologic and temporal influences. The upper few centimeters of the soil serve as the interface with the atmosphere and influence physical phenomena such as infiltration, evaporation, radiative exchange, erosion and runoff. This layer also contains the greatest mass of organic matter and the largest concentration of microbial organisms; it is the zone where biological transformations are mostly accomplished, resulting in gaseous emissions and altered chemical species.

Traditionally, two research approaches have been followed in soil science: 1) soil taxonomy and 2) process-oriented studies of rates of mass and energy transfer. Over the last 100 years, significant information on soil characteristics has been gathered, catalogued and differentiated following the first approach. This taxonomic information, available in some form for almost every location on the Earth, is used in wide-ranging endeavors such as managing soils for site-specific purposes, distinguishing biomes, planning community development, and establishing taxation policies. Although comprehensive, this information is static. It is of little use in dynamic studies of the soil-atmosphere interface without corresponding information about the relationships between soil characteristics and fluxes in the system. The use of "pedotransfer functions" (e.g., Bouma and Anderson, 1973; Wosten and van Genuchten, 1988; Tietje and Tapkenhinrichs, 1993) which relate static soil characteristics to dynamic soil variables shows promise as a means to exploit the huge worldwide taxonomic database, but has not yet directly addressed its utility at the soil-atmosphere interface.

The second approach attempts to quantify the transfer and retention of matter and energy in soils. It may be said that soil is unique amongst all materials in the universe with respect to its transmission properties. Buckingham (1907) clearly recognized that the analogy of soil water properties to those of electricity and heat was imperfect. For the latter, electrical and thermal properties are practically independent of the amount of current or heat being transmitted,

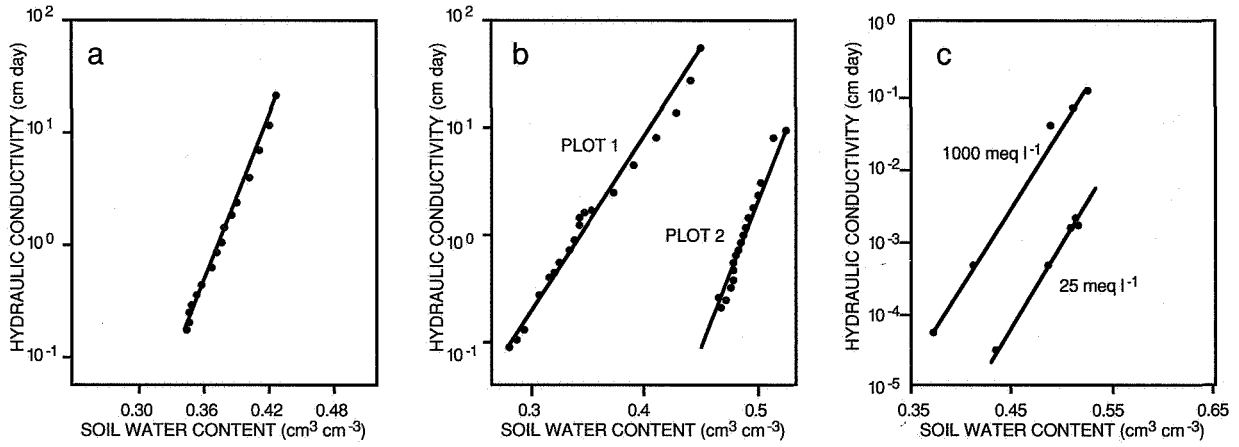


Figure 6. a) Field-measured values of soil hydraulic conductivity versus soil water content. b) Soil hydraulic conductivity as a function of soil water content measured at the same soil depth at two locations 50 m apart. c) Soil hydraulic conductivity as a function of soil water content with different water quality.

whereas soil water properties depend strongly upon the soil water content. Figure 6a shows the dependent behavior of hydraulic conductivity upon soil water content. As the water content decreases from 0.42 to 0.36 cm^3cm^{-3}, the hydraulic conductivity decreases 10-fold. Indeed, the hydraulic conductivity decreases 10 million times as the soil dries from water saturation to complete dryness. This unique attribute is a practical benefit in that it accounts for a soil's ability to rapidly absorb and retain rainfall under a variety of initial and local conditions. However, this attribute increases the difficulty of obtaining solutions of Richards equation and markedly affects our ability to deal with the naturally occurring variations of soil properties across a landscape. In Figure 6b, the unsaturated hydraulic conductivity measured at two different locations separated by a distance of only 50 m is plotted against soil water content. Note that the two curves in Figure 6b differ by nearly two orders of magnitude for the same water content, whereas random variations of field-measured soil water content typically range ± 0.05 cm^3cm^{-3}. Such variability within a taxonomic mapping unit explains why estimates of the hydraulic conductivity, even at short distances, have an uncertainty of 100-fold!

Water in the soil is not pure, but a solution of water and dissolved solid and gaseous constituents. Moreover, soil water cannot be considered simply as ordinary water with a few dissolved solutes, since soil water properties are intimately linked to the chemical and physical properties of the solid phase on which it is sorbed. The impact of this linkage hinges on the amount of water that is in the soil and on the mineralogical composition and particle size distribution of the solid phase. The physical properties of soil water may differ at times markedly from those of water that fills the relatively large pores of highly permeable ground water aquifers because water is a strong dipole and is readily influenced by the net surface charge density of the soil particles and the numbers and kinds of dissolved constituents. Solution ions satisfy the surface charge on soil particles caused by substitution of one element for another in the crystal lattice of clay minerals by several mechanisms. The net surface charge of an assemblage of soil particles gives rise to an electrical field that affects the distribution of cations and anions within the water films. It may also change the configuration and properties of the water close to particle surfaces. As the soil water content decreases, the cations and anions are forced to occupy a space limited by the thickness of the water films on the soil. The effect of total salinity on the unsaturated hydraulic conductivity is illustrated in Figure 6c. A solution of 1000 $meq{\cdot}l^{-1}$ $CaCl_2$

percolating through a soil sample resulted in the upper curve yielding values of the hydraulic conductivity more than one order of magnitude greater than those when a water containing only 25 $meq \cdot l^{-1}$ passed through the soil. Hence, the quality of the soil water, not yet incorporated into any theory of water transport, must be included in models of the land-atmosphere interface. Additional theoretical considerations not fully understood are those of hysteresis of the soil water retention function, the temperature dependency of soil water properties and the transport of water in both vapor and liquid phases under isothermal and nonisothermal conditions.

Segmented, disciplinary approaches in soil science and hydrology have contributed to our lack of theoretical and experimental understanding of the unsaturated zone at the land-atmosphere interface. The puzzle over spatial and temporal sampling requirements for a soil attribute persists, probably owing to our inadequate characterization of spatial and temporal variances associated with measurement as well as soil taxonomy. Remote sensing of surface soil moisture, with its spatial coverage and temporal sampling, offers an opportunity to advance our understanding of soil processes as well as to contribute to hydrology, meteorology, climatology, ecology and other disciplines where soil moisture is a state variable. We also expect that having access to remotely sensed estimates of soil moisture will provide an opportunity for improving ground-based instrumentation.

Issues which can be addressed through experimentation and analysis are plentiful. Can current taxonomic soil information now available for all continents be used for estimating soil moisture at different temporal and spatial scales? Can deficiencies of present-day pedotransfer functions to estimate soil water retention and transfer parameters be improved with remotely sensed data? We envision that remotely sensed data can be used to quantify covariance structures of soil water properties. We should be able to identify scales of observation most useful and informative for different soil and landscape processes consistent with soil taxonomy and their application.

We should be able to relate correlation lengths of surface and profiles of soil moisture to periods of precipitation and evaporation. Moreover, we need to find a useful covariance structure between soil-water properties and those associated with water and energy fluxes at the soil-atmosphere interface. Vertical and horizontal fluxes of energy and mass in the gaseous and liquid phases below the soil surface should be ascertained from surface soil moisture distributions. A question to be answered is, "Can *effective* hydraulic properties of the lower soil profile be derived from areal integration of the temporal change in the surface soil moisture, combined with the use of inverse methods?"

Soil microbes and invertebrates, responsible for transforming carbon and nitrogen occurring in inorganic and organic soil materials, are the primary species that provide nutrients available to plants and animals, and produce and consume methane, CO_2 and other gases important to global climate. Changes in land use alter fluxes of carbon and greenhouse gases through modifications of vegetative patterns that impact directly on microbial communities in terms of diversity and their functioning at the land-atmosphere interface of terrestrial ecosystems. What are the state variables of microbial populations and how are they related to surface soil moisture distributions? We envision water content distributions near the soil surface at various scales of space and time to enhance research in soil microbiology. We expect to find ways of quantifying rates of microbially induced transformations of organic materials linked with surface soil water distributions. We should be able to predict changes of microbial growth and metabolism associated with surface soil water distributions at different scales of time. In addition to

examining their life processes related to greenhouse gases, investigations of the mobility and persistence of soil borne disease organisms relating to surface soil water distributions could improve epidemiological technology.

The opportunity to use remote sensing of surface soil water content to enhance our understanding of soil science and its application to regional and global environmental management appear imminent. We urge the development of a scientific and experimental plan as a follow-up to this Workshop.

II.3. Ecology

Participants: C. Field, J. Norman, S. Running, C. Vorosmarty, D. Wickland

Soil moisture, a dominant controller of ecosystem processes, exerts its effects at a range of time scales (Figure 7). At the long extreme, soil moisture plays a critical role in soil formation (Jenny, 1980). The soils and moisture thereof influence ecosystem processes at time scales of years to decades through effects on nutrient availability and on the kinds of plants that are successful on a site. While rates of production, decomposition, nutrient cycling, and other ecosystem processes overlap between different kinds of ecosystems, effects correlated with the

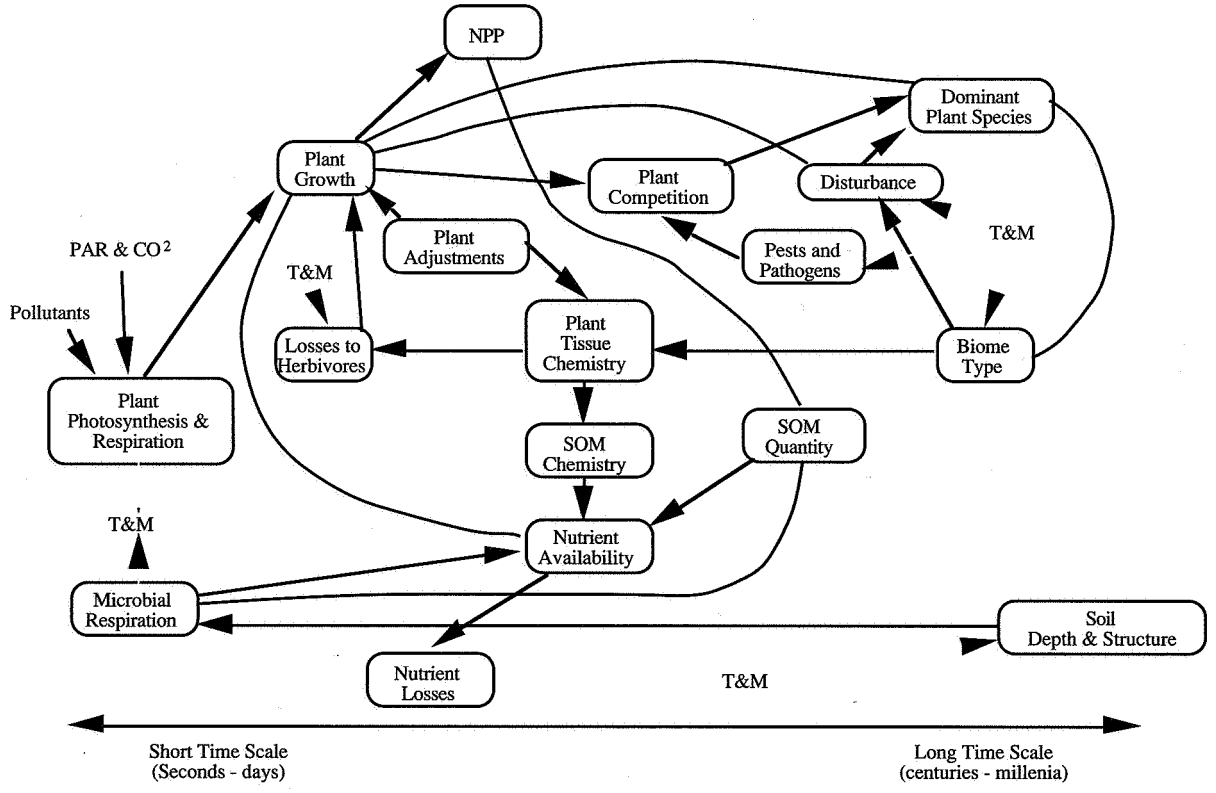


Figure 7. Temporal Scales of Ecological Processes.

kind of ecosystem present on a site (e.g. evergreen conifer forest, savanna, grassland) capture much of the meaningful variation. At time scales of days to months, soil moisture controls the development of the plant canopy and the physiological activities of the plants, decomposers and animals.

Moisture, expressed as either soil moisture or as a function of precipitation, is a key variable in nearly all of the major ecosystem models, ranging from simple climate-driven models (e.g. Lieth, 1975), to sophisticated ecosystem simulators (e.g. Melillo et al., 1993, Running and Hunt, 1993). For the few models that do not directly use moisture as a control, its effects are captured indirectly. For example, models that calculate net primary production from a satellite vegetation index or a measure of total absorbed radiation capture moisture effects in the vegetation index (Ruimy et al., 1994), the production efficiency (Field et al., 1995), or both. Calculations based on averages for different biomes and the distributions of the biomes (Whittaker and Likens, 1975) incorporate implicit effects of moisture in both terms.

Vegetation is so sensitive to moisture that the kind of ecosystem present on a site is a very useful index of the long-term (decades to centuries) history of soil moisture. Yet, because ecosystem boundaries do not change quickly, they provide little information about current soil moisture or even soil moisture over the last year. Parameters like leaf area index or absorbed radiation are more sensitive to short-term fluctuations, but even these are adjusted over periods of months rather than days or weeks. For problems that require assessing average soil moisture over long periods, structural aspects of the ecosystem are very useful integrators. For problems that require the current soil moisture, measures with a basis in energy balance, such as indices based on a vegetation index and canopy temperature (Nemani and Running, 1989), are useful but always incomplete.

Although ecosystem processes regulate soil moisture and contribute to its spatial heterogeneity, it should be noted that a mechanistic understanding of the relationship between soil water content and plant response remains elusive. Thus, from an ecological perspective, a fundamental understanding of plant water stress, in addition to technical limitation in measuring the soil water content, demands urgent attention.

Ecosystems differ greatly in the depth distribution over which plants extract water from the soil. Roots are shallow in many grasslands and deeper in most forests and shrublands (Davis and Mooney, 1985). Moisture extraction from depths of greater than two meters appears to play a critical role in the moisture balance of plantations in the Atacama desert (Mooney et al., 1980), Amazon rainforests (Nepstad et al., 1994) and Great Basin shrublands (Caldwell and Richards, 1989). In some multi-species communities, plants avoid direct competition by emphasizing water extraction from different depths in the soil (Davis and Mooney, 1986). In these and perhaps most ecosystems, soil moisture near the land surface is often a poor index of water availability for plants. Because plants draw water from a range of depths in the soil, large-scale measures of the water available to plants in natural communities are likely to be most successful if measurements are at least partly based on plant characteristics.

Nutrient cycling, on the other hand, is often concentrated near the surface of the soil, with many of the nutrients required by plants released from the decomposition of fallen leaves (Schlesinger, 1991). Since nutrient release is a dominant controller of plant growth in much of the world (Vitousek and Howarth, 1991), remote sensing of soil moisture near the surface may be an important asset for large-scale estimates of nutrient availability.

Vast tracts of land around the world are subject to either permanent or seasonal inundation. The dynamics of plant growth, soil decomposition, and nutrient cycling are sensitive to waterlogging through changes in redox potential. Also, the water status of wetland soils has been shown to be a key control over the emission of radiatively important trace gases such as methane and nitrous oxide. With the capacity to penetrate vegetative canopies, active microwave remote sensing can help monitor the onset and recession of riverine flooding, waterlogging of soils, and permafrost dynamics. Passive microwave techniques can also contribute to the monitoring over large, openly inundated areas.

II.4. Meteorology

Participants: R. Avissar, W. Brutsaert, P.C.D. Milly, M. Parlange, R. Pielke

From the meteorological perspective, the significance of physical and biophysical interaction between the atmosphere and the land lies with the hydrological and ecological processes of the land as *modulated* by soil moisture. At the shorter time scale, under certain atmospheric conditions (e.g., Ek and Mahrt, 1994), evaporation from the soil exerts competing influences on boundary layer cloud development in that it reduces boundary layer growth but increases boundary layer moisture. Cloud-reduction of solar energy reaching the surface reduces heating of the soil which feeds back upon the evaporation. At the longer time scale, although the cycle of El Nino/Southern Oscillation (ENSO) is the dominant mode of interannual variability, variations in land-surface conditions can produce significant changes in extratropical atmospheric circulation in summer seasons and monthly averaged temperatures over land (e.g., Shukla and Mintz, 1982; Manabe and Wetherald, 1987, Huang et al., 1995). Recent observational studies (e.g., Betts and Ball, 1995) have further clarified the influence of soil moisture on the diurnal cycle of the boundary layer over land during summer.

Out of the lack of operational observations of soil moisture has arisen the notion of "soil wetness" in the modeling community. Soil wetness refers to the amount of soil water computed from a land surface model (e.g., a soil-vegetation-atmosphere transfer, or SVAT, scheme); the SVAT scheme can either use atmospheric observations or be made to numerically interact with an atmospheric model in a prognostic or diagnostic setting. In fact, recent improvements in the characterization of land surface moisture and temperature states and vegetation in numerical weather prediction models have shown a significant impact on forecast skills (e.g., Beljaars et al., 1993; Viterbo and Beljaars, 1995). A number of sensitivity studies using atmospheric general circulation models (GCM's) have also shown that the simulation and prediction of the monthly and seasonal surface temperature and rainfall over land and those of the mean diurnal cycle are quite sensitive to the specification of the initial land moisture (e.g., Cook and Gnanadesikan, 1991; Betts et al., 1994).

It is important to recognize that the "soil wetness" calculated for a given atmospheric forcing is model-dependent; the soil wetness is used primarily to calculate the water and energy fluxes between the land surface and the atmosphere and is therefore meaningful only within the context of a particular hydrological or ecological parameterization. Different SVAT models can give different values of soil wetness while having similar estimates of water and energy

exchange. Verification of modeled variables with actual measurements, though frequently practiced in geophysics, is particularly difficult with soil moisture owing to the lack of adequate conceptual or theoretical tools for scaling. Thus, model uncertainty in characterizing or predicting soil wetness will remain unless a consistent space-time estimator for soil moisture is available and a physically-based definition is broadly accepted.

Also of importance to meteorology is the heterogeneity evident in natural landscape and micrometeorological conditions. The juxtaposition of different land surface conditions can result in inland breezes (e.g., farm or irrigation breeze, forest breeze, etc.) and organized mesoscale circulation. Many models and analytic studies have been used to suggest the importance of the impact of patchiness of landscape on areal turbulent fluxes (Ookouchi et al., 1984; Andre et al., 1990; Avissar and Verstraete, 1990; Cotton and Pielke, 1992; Chang and Wetzel, 1991). However, observational analyses have been less abundant; examples include Segal et al., 1988; Smith et al., 1992; and Mahrt et al., 1994. It is generally agreed that the modulation of turbulent fluxes and the development of mesoscale circulation due to surface heterogeneity depend on ambient flow characteristics as well as the horizontal scale of the heterogeneity itself.

It should be noted that the spatial and temporal sampling requirements of soil moisture could be quite different for different objectives. Soil moisture integrated over the entire soil depth at a horizontal resolution of 100 km and a temporal resolution of 1 month might be sufficient for climate investigations; however, finer spatial and temporal resolutions are probably required for improved weather forecasts. For the purpose of developing and evaluating parameterization schemes in atmospheric and hydrologic models, experimental data at high spatial and temporal resolutions are necessary. Reliable observations of soil moisture, both in situ and remotely sensed, as well as complementary data can be obtained via carefully coordinated field experiments. The predominance of surface heterogeneity presents challenges for the sampling and monitoring of soil moisture at the large scale and for the parameterization of infiltration and evapotranspiration. A coherent theoretical basis and conceptual framework for sampling and monitoring in the presence of spatial heterogeneity needs to be developed and made an integral part of experimental planning.

III. Spatial and Temporal Variability and Sampling

Participants: E. Foufoula-Georgiou, T. Jackson, E. Njoku, G. North, F. Ulaby, J. Valdes, J. van Zyl

The variability found in soil moisture fields results, on the one hand, from the variability of precipitation, evapotranspiration, percolation, lateral flow and topographic control of water transport, and on the other hand, from the heterogeneous hydraulic characteristics of the porous medium itself. The observation and determination of soil moisture distributions must therefore be based on robust sampling strategies. Furthermore, the precise knowledge of sensor sensitivities to natural variability in the fields of view needs to be understood and integrated with the design of observing systems and respective retrieval algorithms.

How often in time and how densely in space do we need to sample in order to resolve the essential statistical features of the soil moisture field? Since no sampling scheme can make observations of a field continuously in both space and time, there are invariably errors and biases associated with estimating spatial and temporal averages of a continuous field from discrete measurements. The errors depend on the observational design and the spatial and temporal variability of the underlying field itself.

Prior to implementing a soil moisture observing system, research that addresses the following scientific issues is imperative:

1. The footprints of space-borne microwave sensors, either active or passive, are large compared to the scale of variability in soil moisture fields. Thus, it is important to understand the relation between the sensor measurement (in terms of either reflectivity or irradiance) and the heterogeneous make-up of the surface properties within the field of view. For example, does the sensor measure a weighted-average condition of a heterogeneous field according to the antenna pattern or is it sensitive to a subarea within the field of view which has the maximum reflectivity or irradiance?
2. The spatial-temporal scales of soil moisture variability need to be determined in the context of particular research and operational applications. The requirements for soil moisture measurements are different for global climate models, numerical weather prediction, river forecast models, ecological models, biogeochemical studies and land-use or agricultural planning. What spatial-temporal scales are important to resolve for each application? Some of the scientific considerations are outlined in Section II; they should be further supported by detailed analyses of experimental data of sufficient duration and spatial coverage and numerical simulation studies.
3. It would be wise to evaluate the errors associated with different sampling design configurations with a given estimate of the space-time covariance structure of the soil moisture field. The errors can be estimated using techniques based on second- or higher-order statistical properties given the space-time covariance structure of a soil moisture field. However, a comprehensive knowledge of the covariance structure of the soil moisture fields may require extensive analyses of experimental data and model-simulated fields.

4. Any spatial-temporal averaging or aggregation of the soil moisture field will undoubtedly alter its statistical description; that is, the soil moisture statistical structure is scale-dependent. In addition to quantifying the variability of soil moisture at a range of spatial-temporal scales, it is important to understand how statistical properties of soil moisture at one scale of aggregation relate to those at another scale. An important scientific question is whether there are any scale-invariant relationships which could be useful in the parameterizations of soil moisture at a range of scales of interest.

The research topics outlined above are each nontrivial and could lead to extensive research and field programs. Investigations into these topics contribute to the necessary scientific basis which needs to be in place before a space-borne mission can be justified. The full understanding of sampling and sensor-sensitivity issues must be integrated with the requirements of the user community in preparation for a satellite mission.

IV. Conclusions

The assembly of hydrologists, meteorologists, ecologists, and soil scientists at the Tiburon Workshop reaffirmed the common concern about the monitoring of soil moisture. Although the scales of concern vary from one inquiry to another, the spatial and temporal distributions of soil moisture and temperature are fundamental to all disciplines. In the absence of a comprehensive set of observations, surrogate measurements and modeled estimates have been devised as substitutes, which limits the possibility of verification and intercomparison amongst disciplines. Despite such practices, sensitivity studies using numerical models suggest that monitoring of soil moisture across large spatial scales and over long periods of time should benefit both research and applications.

The difficulty with the measurement of soil moisture and the understanding of its dynamics has often been attributed to the heterogeneity of soil properties and land surface attributes. However, at the large scale, the complicating factor in soil moisture dynamics also lies with the complex control of the land surface energy and water balance by the atmosphere and the soil; this control is further modulated by plant activities in the root zone. Observing and understanding the switch between the control by the atmosphere and the control by the soil is central to the design and implementation of any monitoring system of soil moisture.

Recent progress in passive and active microwave remote sensing of surface soil moisture was recognized at the Workshop. In passive remote sensing, the technique of aperture synthesis has been successfully demonstrated with an airborne L-band thinned array radiometer, ESTAR; this demonstration offers promising prospects for a space-borne radiometer system at very low microwave frequencies. In active remote sensing, the successful flights of SIR-C/X-SAR on the shuttle and ESA ERS-1 satellite have also allowed the analysis of radar data in relation to surface soil moisture. Also recognized was the complementarity of different approaches in remote sensing (e.g., passive and active microwave, optical, and thermal infrared), which is the key to achieving the spatial and temporal coverage desired by the hydrologists, meteorologists, soil scientists and ecologists. A modeling and analysis framework is needed for investigating soil moisture dynamics. The definition of a space-time estimator of soil moisture, including estimates of uncertainty or error, is essential in making optimal use of various *in situ* and remote measurements of soil moisture, as well as in identifying modeled variables with actual measurements.

With recent advances in both knowledge and practice, an opportunity is clearly at hand to establish a comprehensive scientific framework for the global monitoring of soil moisture. A thorough understanding of the sensor and related algorithms and a rigorous argument for required sampling and accuracy are necessary elements of a scientific framework that supports and sustains the development of a global monitoring system. NASA should promote and ensure the interplay amongst sensor and technique development, field experimentation, and modeling and analysis.

NASA is urged to support several parallel, but joint activities. Since the soil moisture profile represents the essential variable, the feasibility of inferring the profile from remotely sensed surface measurements over a range of meteorological, climatic, topographic and vegetative conditions needs to be examined. The value and uncertainty of converting soil taxonomic information into hydraulic properties of the soil should also be examined. The scientific basis for

gainful use of remote measurements of surface soil moisture should be firmly established. Algorithm development and sampling design should be examined in light of sensor sensitivity and the heterogeneity of the underlying field. The new technique of synthetic aperture radiometry should be exploited for mission design, possibly in conjunction with other active and passive sensors.

V. References

Andre, J. C., P. Bougeault, and J. P. Goutorbe, Regional estimates of heat and evaporation fluxes over non-homogeneous terrain: Examples from the HAPEX-MOBILHY Programme, *Bound. Layer Meteor., 50*, 77-108, 1990.

Avissar, R., and M. M. Verstraete, The representation of continental surface processes in atmospheric models, *Rev. Geophys., 28*, 35-52, 1990.

Beljaars, A. C. M., J.-F. Mahfouf, and J. Noilhan, Sequential assimilation of soil moisture from atmospheric low-level parameters, Part II: Implementation in a mesoscale model, *J. Appl. Meteor., 32*, 1352-1364, 1993.

Bell, K. P., B. J. Blanchard, T. J. Schmugge, and M. W. Witczak, Analysis of surface moisture variations within large-field sites, *Water Resour. Res., 16*(4), 796-810, 1980.

Betts, A. K., J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. Viterbo, Coupling between land-surface, boundary-layer parameterizations and rainfall on local and regional scales: lessons from the wet summer of 1993. Fifth Conf. on Global Change Studies, Amer. Meteor. Soc. 74th Annual Meeting, Jan. 23-28, 1994, Nashville, TN, 174-181, 1994.

Betts, A. K. and J. H. Ball, The FIFE surface diurnal cycle climate, *J. Geophys. Res.*, (in press), 1995.

Bouma, J., and J. L. Anderson, Relationships between soil structure characteristics and hydraulic conductivity, in *Field Soil Moisture Regime, Special Publ. 5*, edited by R. R. Bruce, pp. 77-105, ASA and SSSA, Madison, Wisconsin, 1973.

Brubaker, K.L. and D. Entekhabi, Nonlinear dynamics of water and energy balance in land-atmosphere interaction, MIT Department of Civil and Environmental Engineering Technical Report No. 341, 147 pp., Cambridge, MA, 1994.

Buckingham, E., Studies on the movement of soil moisture, *Bull. 38*, USDA Bureau of Soils, Washington, DC, 1907.

Caldwell, M. M., and J. H. Richards, Hydraulic lift: water efflux from upper roots improves effectiveness of water uptake by deep roots, *Oecologia, 79*, 1-5, 1989.

Chang, J., and P. J. Wetzel, Effects of spatial variations of soil moisture and vegetation on the evolution of a prestorm environment: A numerical case study, *Mon. Wea. Rev., 119*, 1368-1390, 1991.

Cognard, A.-L., C. Loumagne, M. Normand, P. Olivier, C. Ottle, D. Vidal-Madjar, S. Louahala, and A. Vidal, Evaluation of the ERS 1/synthetic aperture radar capacity to estimate surface soil moisture: Two-year results over the Naizin watershed, *Water Resour. Res., 31*(4), 975-982, 1995.

Cook, K. H., and A. Gnanadesikan, Effects of saturated and dry land surfaces on the tropical circulation and precipitation in a general circulation model, *J. Climate, 4*, 873-889, 1991.

Cotton, W. R., and R. A. Pielke, Human impacts on weather and climate, *Geophysical Science Series 2*, ASTeR Press, Fort Collins, Colorado, 288pp., 1992.

Davis, S. D., and H. A. Mooney, Water use patterns of four co-occuring chaparral shrubs, *Oecologia, 70*, 172-177, 1986.

Davis, S. D., and H. A. Mooney, Comparative water relations of adjacent California shrub and grassland communities, *Oecologia, 66*, 522-529, 1985.

Dubois, P. C., J. van Zyl, and E. T. Engman, Measuring soil moisture with imaging radars, *IEEE Trans., Geosci. Remote Sensing, 33*(4), 915-926, 1995.

Ek, M., and L. Mahrt, Daytime evolution of the relative humidity at the boundary layer top, *Mon. Wea. Rev., 122*, 2710-2721, 1994.

Entekhabi, D., H. Nakamura, and E. G. Njoku, Solving the inverse problem for soil moisture and temperature profiles by sequential assimilation of multifrequency remotely sensed observations, *IEEE Trans. Geosci. Remote Sensing, 32*(2), 438-448, 1994.

Field, C. B., J. T. Randerson., C. M. Malmstrum, and C. S. Potter, Ecological controls on net primary production: Lessons from global models, in *Scaling Up*, edited by P. van Gardingen, G. Foody, and P. Curran, (in press), Cambridge University Press, Cambridge, 1995.

Goodrich, D. C., T. J. Schmugge, T. J. Jackson, C. L. Unkrich, T. O. Keefer, R. Parry, L. B. Bach, and S. A. Amer, Runoff simulation sensitivity to remotely sensed initial soil water content, *Water Resour. Res., 30*(5), 1393-1405, 1994.

Greacen, E. L., *Soil water assessment by the neutron method*, CSIRO, Melbourne, Australia, 140pp., 1981.

Hollinger, S. E., and S. A. Isard, A soil moisture climatology for Illinois, *J. Climate, 7*, 822-833, 1994.

Huang, J., H. M. van den Dool, and K. P. Georgakakos, Analysis of model-calculated soil moisture over the U. S. (1931-93) and applications in long-range temperature forecasts, submitted to *J. Climate*, 1995.

Jackson, T. J., and T. J. Schmugge, Vegetation effects on the microwave emission of soils, *Remote Sens. Environ., 36*, 203-212, 1991.

Jackson, T. J., D. M. LeVine, A. J. Griffs, D. C. Goodrich, T. J. Schmugge, C. T. Swift, and P. E. O'Neill, Soil moisture and rainfall estimation over a semiarid environment with the ESTAR microwave radiometer, *IEEE Trans. Geosci. Remote Sensing, 31*(4), 836-841, 1993.

Jackson, T. J., E. T. Engman, D. M. LeVine, T. J. Schmugge, R. Lang, E. Wood, and W. Teng, Multitemporal passive microwave mapping in MACHYDRO'90, *IEEE Trans. Geosci. Remote Sensing, 32*(1), 201-206, 1994.

Jackson, T. J., D, M. LeVine, C. T. Swift, T. J. Schmugge, and F. R. Schiebe, Large area mapping of soil moisture using the ESTAR passive microwave radiometer in Washita'92 experiment, *Remote Sens. Environ., 53*, 23-37, 1995.

Jenny, H., *The soil resource*, Springer-Verlag, New York, 1980.

Kerr, Y., and E. G. Njoku, A semi-empirical model for interpreting microwave emission from semiarid land surfaces as seen from space, *IEEE Trans. Geosci. Rem. Sens., 28*, 384-393, 1990.

Klute, A., *Methods of soil analysis*, American Society of Agronomy and Soil Science Society of America, Madison, Wisconsin, 1188pp., 1986.

Kuhnel, V., Dooge, J. C. I., Sander, G. C., and J. P. J. O'Kane, Duration of atmosphere-controlled and soil-controlled phases of infiltration for constant rainfall at a soil surface, *Annales Geophysicae, 8*(1), 11-20, 1990.

Lawford, R. G., An overview of soil moisture and its role in the climate system, in *Soil Moisture: Modelling and Monitoring for Regional Planning, NHRI Symposium Proceedings 9*, edited by F. J. Eley, R. Granger, and L. Martin, 1-12, Saskatoon, Saskatchewan, Canada, 1992.

LeVine, D. M., M. Kao, A. B. Tanner, C. T. Swift, and A. Griffis, Initial results in the development of a synthetic aperture microwave radiometer, *IEEE Trans. Geosci. Remote Sensing, 28*, 614-619, 1990.

Lieth, H., Modeling the primary productivity of the world, in *Primary Productivity of the Biosphere,* edited by H. Lieth and R. H. Whittaker, pp. 237–263, Springer-Verlag, New York, 1975.

Mahrt, L., J. Sun, D. Vickers, J. I. MacPherson, J. R. Pederson, and R. L. Desjardins, Observations of fluxes and inland breezes over a heterogeneous surface, *J. Atmos., Sci., 51*(17), 2484-2499, 1994.

Manabe, S., and R. T. Wetherald, Large scale changes in soil wetness induced by an increase in atmospheric carbon dioxide, *J. Atmos. Sci., 44*, 1211-1235, 1987.

McNab, A. L., and T. R. Karl, Climate and droughts, *USGS Water Supply Paper 2375*, 89-95, 1989.

Melillo, J. M., D. W. Kicklighter, A. D. McGuire, B. Moore III, C. J. Vorosmarty, and A. L. Grace, Global climate change and terrestrial net primary production, *Nature, 363*, 234-240, 1993.

Mooney, H. A., S. L. Gulmon, P. W. Rundel, and J. Ehleringer, Further observations on the water relations of Prosopis tamarugo of the northern Atacama desert, *Oecologia, 44*, 177-180, 1980.

National Research Council, *Opportunities in hydrologic sciences*, National Academy Press, Washington, DC, 348pp., 1991.

National Research Council, *A decade of international climate research: The first ten years of the World Climate Research Program*, National Academy Press, Washington, DC, 59pp., 1992.

Nemani, R., and S. W. Running, Estimating regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data, *J. Climate Appl. Meteor., 28*, 276-284, 1989.

Nepstad, D. C., C. R. de Carvalho, E. A. Davidson, P. H. Jipp, P. A. Lefebvre, G. H. Negreiros, E. D. da Silva, T. A. Stone, S. E. Trumbore, and S. Vieira, The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures, *Nature, 372*, 666-669, 1994.

Njoku, E. G., and J. A. Kong, Theory for passive microwave remote sensing of near-surface soil moisture, *J. Geophys. Res., 82*, 3108-3118, 1977.

North, G. R., and S. Nakamoto, Formalism for comparing rain estimation designs, *J. Atmos. Ocean. Tech., 6*, 985-992, 1989.

Oh, Y., K. Sarabandi, and F. T. Ulaby, An empirical model and an inversion technique for radar scattering from bare soil surfaces, *IEEE Trans. Geosci. Remote Sensing, 30*(2), 370-381, 1992.

Ookouchi, Y., M. Segal, R. C. Kessler, and R. A. Pielke, Evaluation of soil moisture effects on the generation and modification of mesoscale circulations, *Mon. Wea. Rev., 112*, 2281-2292, 1984.

Ripley, E. A., Soil moisture patterns on the eastern Canadian prairies, in *Soil Moisture: Modelling and Monitoring for Regional Planning, NHRI Symposium Proceedings 9*, edited by F. J. Eley, R. Granger, and L. Martin, 89-96, Saskatoon, Saskatchewan, Canada, 1992.

Ruimy, A., G. Dedieu, and B. Saugier, Methodology for the estimation of terrestrial net primary production from remotely sensed data, *J. Geophys. Res.*, 99, 5263-5284, 1994.

Running, S. W., and E. R. Hunt, Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models, in *Scaling Physiological Processes: Leaf to Globe*, edited by J. R. Ehleringer and C. B. Field, pp. 141-158, Academic Press, San Diego, 1993.

Salvucci, G. D., and D. Entekhabi, Equivalent steady soil moisture profile and the time compression approximation in water balance modeling, *Water Resour. Res., 30*(1), 2737-2749. 1994.

Schlesinger, W. H., *Biogeochemistry: An Analysis of Global Change*, 443 pp., Academic Press, San Diego, 1991.

Schmugge, T. J., Remote sensing of soil moisture, in *Hydrological Forecasting*, edited by M. G. Anderson and T. P. Burt, pp. 101-124, John Wiley, New York, 1985.

Schmugge, T. J., T. J. Jackson, and H. L. Mckim, Survey of methods for soil moisture determination, *Water Resour. Res., 16*(6), 961-979, 1980.

Schmugge, T. J., T. J. Jackson, W. P. Kustas, R. Roberts,R. Parry, D. C. Goodrich, S. A. Amer, and M. A. Weltz, Push broom microwave observations of surface soil moisture in Monsoon'90, *Water Resour. Res., 30*(5), 1321-1327, 1994.

Schulin, R., J. Fluhler, H. M. Selim, B. Sevruk, and P. J. Wierenga, Soil moisture, in *Snow Cover Measurements and Areal Assessment of Precipitation and Soil Moisture, Operational Hydrology Report 35*, edited by B. Sevruk, pp. 221-283, World Meteorological Organization, Geneva, Switzerland, 1992.

Segal, M., R. Avissar, M. C. McCumber, and R. A. Pielke, Evaluation of vegetation effects on the generation and modification of mesoscale circulations, *J. Atmos. Sci., 45*, 2268-2292, 1988.

Shukla, J., and Y. Mintz, The influence of land surface evaporation on the earth's climate, *Science, 215*, 1498-1501, 1982.

Smith, E. A., A. Y. Hsu, W. L. Crosson, R. T. Field, L. J. Fritschen, R. J. Gurney, E. T. Kanemasu, W. P. Kustas, D. Nie, W. J. Shuttleworth, J. B. Stewart, S. B. Verma, H. L. Weaver, and M. L. Wesely, Area-averaged surface fluxes and their time-space variability over the FIFE experimental domain, *J. Geophys. Res., 97*(D17), 18599-18622, 1992.

Stofan, E. R., D. L. Evans, C. Schmullius, B. Holt, J. J. Plaut, J. van Zyl, S. D. Wall, and J. Way, Overview of results of Spaceborne Imaging Radar-C, X-band Synthetic Aperture Radar (SIR-C/X-SAR), *IEEE Trans. Geosci. Remote Sensing, 33*(4), 817-828, 1995.

Swift, C. T., D. M. LeVine, C. S. Ruf, Aperture synthesis concepts in microwave remote sensing of the Earth, *IEEE Trans. Microwave Theory and Techniques, 39*(12), 1931-1935, 1991.

Tietje, O., and M. Tapkenhinrichs, Evaluation of pedo-transfer functions, *Soil Sci. Soc. Am. J., 57*, 1088-1095, 1993.

Topp, G. C., J. L. Davis, and A. P. Annan, Electromagnetic determination of soil water content: Measurement in coaxial transmission lines, *Water Resour. Res., 16*(3), 574-582, 1980.

Ulaby, F. T., R. K. Moore, and A. K. Fung, *Microwave Remote Sensing: Active and Passive*, Vol. I, *Microwave Remote Sensing Fundamentals and Radiometry*, pp. 1-456, Addison-Wesley, Reading, MA, 1981. Vol. II, *Radar Remote Sensing and Surface Scattering and Emission Theory*, pp. 457-1064, Artech House, Norwood, MA, 1982. Vol. III, *From Theory to Applications*, pp. 1065-2162, Artech House, Norwood, MA, 1986.

van de Griend, A. A. and M. Owe, Microwave vegetation optical depth and inverse modelling of soil emissivity using Nimbus/SMMR satellite observations, *Meteor. Atmos. Phys. 54*, 225-239, 1994.

Viterbo, P., and A. C. M. Beljaars, A new land surface parameterization scheme in the ECMWF model and its validation, *J. Climate*, 1995.

Vitousek, P. M., and R. W. Howarth, Nitrogen limitation on land and in the sea: How can it occur?, *Biogeochemistry, 13*, 87-115, 1991.

Whittaker, R. H., and G. E. Likens, The Biosphere and Man, in *Primary Productivity of the Biosphere*, edited by H. Lieth and R. H. Whittaker, pp. 305-328, Springer-Verlag, Berlin, 1975.

Wosten, J. H. M., and M. Th. van Genuchten, Using texture and other soil properties to predict the unsaturated soil hydraulic functions, *Soil Sci. Soc. Am., J., 52*, 1762-1770, 1988.

Appendix A. List of Participants

RONI AVISSAR, Rutgers University
LAWRENCE BAND, University of Toronto
OTTO W. BAUMER, USDA Soil Conservation Service, Lincoln, NE
KEITH BRISTOW, CSIRO Division of Soils, Australia
WILFRIED H. BRUTSAERT, Cornell University
MICHAEL A. CELIA, Princeton University
RICHARD H. CUENCA, Oregon State University
JAMES C. I. DOOGE, University College, Dublin, Ireland
EDWIN T. ENGMAN, NASA Goddard Space Flight Center
DARA ENTEKHABI, Massachusetts Institute of Technology
CHRISTOPHER B. FIELD, Carnegie Institution of Washington, Stanford, CA
EFI FOUFOULA-GEORGIOU, University of Minnesota
KONSTANTINE GEORGAKAKOS, Hydrologic Research Center, San Diego, CA
DAVID C. GOODRICH, USDA Southwest Watershed Research Center, Tucson, AZ
THOMAS J. JACKSON, USDA Hydrology Laboratory, Beltsville, MD
RANDAL D. KOSTER, NASA Goddard Space Flight Center
DENNIS B. MCLAUGHLIN, Massachusetts Institute of Technology
P. C. D. MILLY, USGS and NOAA Geophysical Fluid Dynamics Laboratory
DONALD R. NIELSEN, University of California-Davis
ENI G. NJOKU, Jet Propulsion Laboratory
JOHN M. NORMAN, University of Wisconsin-Madison
GERALD R. NORTH, Texas A&M University
MARC B. PARLANGE, University of California-Davis
ROGER A. PIELKE, Colorado State University
IGNACIO RODRIGUEZ-ITURBE, Texas A&M University
STEVEN W. RUNNING, University of Montana
PETER A. A. TROCH, Ghent University, Belgium
GORO UEHARA, University of Hawaii
FAWWAZ T. ULABY, University of Michigan
JUAN B. VALDES, Texas A&M University
MARTINUS VAN GENUCHTEN, USDA Salinity Laboratory, Riverside, CA
JAKOB VAN ZYL, Jet Propulsion Laboratory
CHARLES VOROSMARTY, University of New Hampshire
ROBERT J. WAGENET, Cornell University
MING-YING WEI, NASA Headquarters
DIANE E. WICKLAND, NASA Headquarters

Appendix B. List of Contributors

GHASSEM ASRAR, NASA Headquarters

ALAN K. BETTS, Pittsford, Vermont

KEITH BEVEN, University of Lancaster, United Kingdom

TOBY N. CARLSON, Pennsylvania State University

CHRISTOPHER DUFFY, Pennsylvania State University

ANTHONY W. ENGLAND, University of Michigan

GEORGE M. HORNBERGER, University of Virginia

L. DOUGLAS JAMES, National Science Foundation

RICK G. LAWFORD, National Hydrology Research Center, Saskatoon, Canada

JEAN-FRANCOIS MAHFOUF, (European Centre for Medium-Range Weather Forecasts, Reading, England)

LARRY MAHRT, Oregon State University

CALVIN T. SWIFT, University of Massachusetts, Amherst

HUUG VAN DEN DOOL, National Meteorological Center

ARTHUR WARRICK, University of Arizona

ERIC F. WOOD, Princeton University

Appendix C. Ground-Based Measurement Techniques of Soil Moisture

Summaries of the direct and indirect methods of measuring or estimating soil moisture can be found in several excellent references, including Schmugge et al. (1980), Klute (1986) and Schulin et al. (1992). Klute is particularly useful for detailed descriptions of ground-based methods. Schmugge et al. and Schulin et al. are more of a summary in form, with emphasis on strengths and limitations of various techniques; Schulin et al. also includes a discussion of error analysis.

Included below are short descriptions of some of the primary methods used in ground-based measurements; remote techniques are included in Appendix D. It should be noted that the various methods, in fact, measure different aspects of the same physical phenomenon, that is, water retained in the soil. The measurements can represent the volumetric or mass concentration in a bulk porous media, the matric pore pressure associated with capillary and hygroscopic forces, the gradients which imply a certain flux rate, or the dielectric constant of a partially saturated porous media. Considering that the strength of remote sensing, whether airborne or spaceborne, lies with ready, large spatial coverage which is so difficult with traditional ground-based methods, the challenge appears to be devising ways to make use of all sources of measurements, necessarily including respective error characteristics, in analysis and/or modeling schemes which appropriately capture the dynamics of the terrestrial component of the water cycle.

Gravimetric techniques

Gravimetric techniques remain the standard method for determining soil water content; all other methods ultimately depend on gravimetric measurements for calibration. Thus, errors in gravimetric measurements are an inherent part of the errors of all other methods.

With this technique, a sample of soil is first removed from the field, weighed as is, then oven dried, and weighed again. The water content is typically expressed as a percentage of the dry soil weight. The volumetric water content is obtained by multiplying the gravimetric water content by the apparent specific gravity or the ratio of bulk density to the density of water. Because of the additional time and expense required for simultaneously determining the bulk density, independent estimates of bulk density are generally used. The error introduced into the volumetric water content from the degree of representativeness of the bulk density sample, as compared to the gravimetric sample, varies inversely with the gravimetric water content (Bell et al., 1980).

The sampling apparatus of the gravimetric method is relatively simple; so is the computation of soil water content. The disadvantages include a) difficulty in obtaining representative samples in a heterogeneous soils, b) difficulty with sampling at depth in rocky soils, c) significant amount of labor for obtaining time series, d) increased relative error with drier soils, and finally e) destruction of the site.

Nuclear techniques

Two types of depth probes have been developed for soil moisture using gamma ray attenuation and neutron scattering; only the neutron scattering method is included here.

The neutron scattering method measures soil moisture indirectly by emitting high-energy (fast) neutrons and monitoring the resultant neutrons slowed down by elastic collisions with the hydrogen atoms in the soil-water matrix. The count of slow neutrons is a function of water content because the energy lost from colliding with hydrogen atoms is far greater than colliding with heavier atoms. The volumetric water content is determined through calibration with gravimetric measurements. A comprehensive discussion of the neutron scattering method can be found in Greacen (1981).

There are two designs of the neutron probe. The depth probe gives the vertical profile of soil moisture if an access tube can be installed; the surface probe gives the moisture content of the top few centimeters of the soil. Both designs allow easy, repeated measurements at the same location whether the water molecules are in solid, liquid or vapor phase. The main disadvantages of this method are a) the soil volume sampled depends on the water content; b) poor vertical resolution limits its utility when studying processes, such as infiltration, percolation, etc. c) depending on the physical and chemical properties, the method may require site-specific calibration; and d) care must be taken to minimize risks to health.

Electromagnetic techniques

Electromagnetic techniques make use of the dielectric properties of moist soil. A variety of sensors, responsive to either resistivity (the imaginary part of the dielectric constant) or polarization (the real part of the dielectric constant), or both, have been constructed. Some of these sensors are designed for *in situ* operation (i.e., implantable); others are to be operated remotely from either an airborne or a spaceborne platform. The latter will be discussed shortly in Appendix D; our immediate attention is on time-domain reflectometry (Topp et al., 1980).

With time-domain reflectometry (TDR), an electromagnetic pulse is emitted into the soil along parallel wave guides (typically, metallic rods); a signal is reflected back, from the ends and along the wave guides, into the instrument. The travel time (or velocity of propagation) of the pulse is proportional to the dielectric constant of the soil in contact with the probes. Because of the large difference between the dielectric constants of water (~80) and dry soil (2-5), the transmission time provides a good measure of the soil water content. A unique calibration curve can be established for a wide range of soil temperature, salinity, bulk density and texture (Topp et al., 1980), although specific calibration may be recommended for heavy clay and organic soils, the reason being that clay and organic soils have a higher specific density of polarized functional surface groups than silt or sand; these polarized groups bind the water molecules at the liquid-solid interface (Schmugge, 1985).

TDR is gaining wide application because of several advantages. First, the sampling volume is a function of probe geometry alone; since it is relatively small, appropriately placed horizontal rods allow relatively high vertical resolution of the soil moisture profile. The measurement is instantaneous, enabling process studies such as infiltration through soils with macropores. Easy vertical installation of the wave guides or rods makes TDR particularly suitable for soil moisture estimates near the surface where the standard neutron probe is not as reliable. The TDR technique can distinguish between liquid water and ice, as well as give simultaneous readings of soil water content and salinity. The only disadvantages are the relatively high cost of the instrument and the need for calibration specific to individual sites.

Tensiometric techniques

A tensiometer consists of a porous cup and a vacuum gage or other pressure-measuring devices such as a pressure transducer. It measures capillary tension or the energy with which water is held by the soil; the reading, or matrix potential, is then converted to soil water content by employing soil water retention curves. The tensiometer is applicable when the soil is moist, with the matrix potential ranging from 0 to -80 kPa; in the drier range, a soil psychrometer or gypsum block is needed.

The tensiometer is relatively easy and inexpensive to design, construct and deploy with minimal disturbance to the soil. A simple reading of saturated or unsaturated condition can be quite useful in determining the water table and sampling depth when conducting soil moisture studies. However, hysteresis associated with the moisture characteristic of a soil complicates the conversion to soil water content which relies on the soil water retention curve. Quantitative measurements of water content or storage in a soil often requires the combined use with other techniques.

Appendix D. Microwave Remote Sensing of Soil Moisture

Microwave remote sensing provides a unique capability for direct observations of soil moisture by exploiting the large difference between the dielectric constant of water (~80 at frequencies below 5 GHz) and that of dry soil (~3.5). Detailed discussion of the theoretical basis and principles of passive and active techniques can be found in a number of excellent references (e.g., Njoku and Kong, 1977; Ulaby et al., 1981, 1982, 1986). The following discussion provides only a brief overview and focuses on current status of the techniques and emerging technologies.

Microwave scattering and emissive properties of bare soils are determined principally by the soil dielectric constant and surface roughness. The dielectric constant is governed primarily by the soil moisture content. Figure D1 shows the relationship between soil dielectric constant (consisting of both real and imaginary parts) and volumetric moisture for different soil types at a frequency of 1.4 GHz; the variation with soil type (i.e. texture) is due to differences in the percentage of water bound to the particle surfaces in the different soils. Derived relationships between soil emissivity or backscattering coefficient and moisture content form the bases for the microwave soil moisture estimation algorithms. The dependence of soil dielectric constant on frequency is illustrated in Figure D2. The penetration depth, defined as the

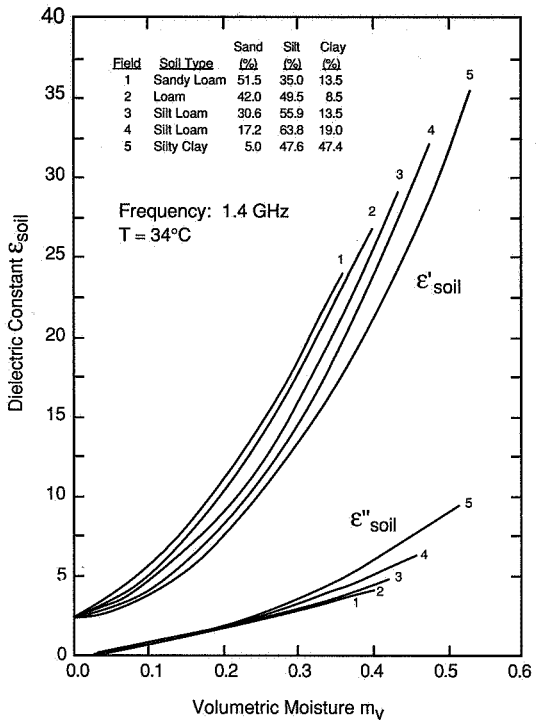

Field Soil Type Sand (%) Silt (%) Clay (%)
1 Sandy Loam 51.5 35.0 13.5
2 Loam 42.0 49.5 8.5
3 Silt Loam 30.6 55.9 13.5
4 Silt Loam 17.2 63.8 19.0
5 Silty Clay 5.0 47.6 47.4
Frequency: 1.4 GHz
T = 34°C
ε'soil
ε"soil
Dielectric Constant εsoil
Volumetric Moisture mv

Figure D1. Dielectric constant as a function of volumetric soil moisture for five soils at 1.4 GHz. The curves have been drawn through measured data points (from Ulaby et al., 1986).

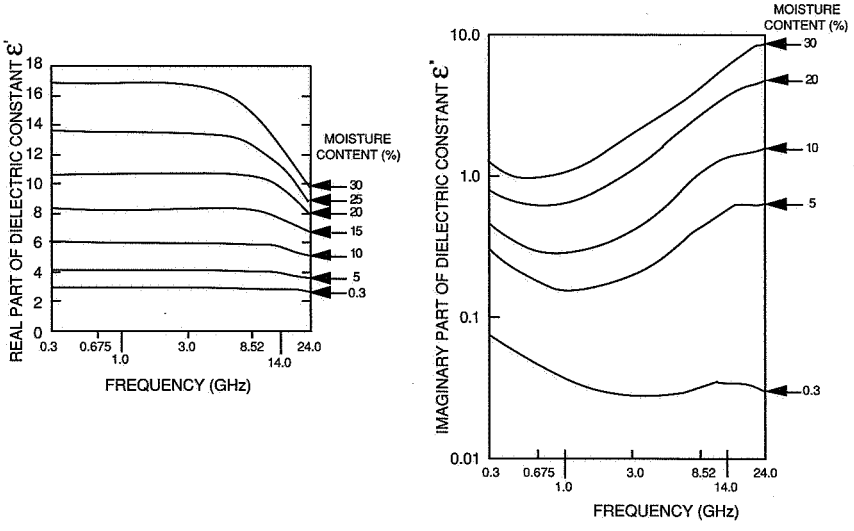


Figure D2. Dielectric constant of sand as a function of frequency and moisture (from Njoku and Kong, 1977).

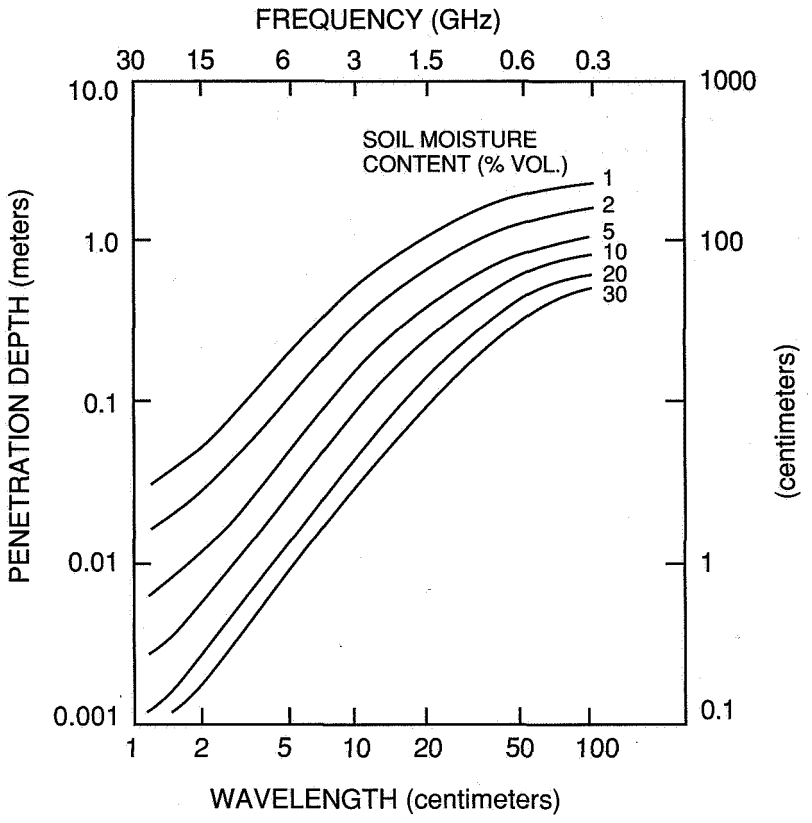


Figure D3. Microwave soil penetration depth as a function of frequency and moisture content (based on data in Figure D2).

distance in the soil over which microwave radiated power is attenuated by a factor of e (=2.718) also depends on the dielectric constant and is shown in Figure D3 as a function of frequency and moisture content. The penetration depth is an indicator of the depth of the surface layer within which changes in moisture content may significantly influence the microwave sensor response. Soil emission and backscattering are also affected by the surface roughness and vegetation cover, hence corrections must be made for these effects in order to retrieve soil moisture from microwave observations. The retrievals become increasingly unreliable as the opacity of the vegetation layer increases and the sensitivity to soil moisture decreases.

Passive techniques

The most practical frequency range for single channel radiometer soil moisture measurements is 1-3 GHz. Longer wavelengths permit better penetration of vegetation cover but lead to larger antenna size requirements. Within this range most studies have focused on 1.4 GHz since this is centered in a protected radio astronomy band with reduced probability of signal contamination from radio-frequency interference. Single-channel measurements require information from other sources to make corrections for vegetation, roughness, temperature and texture (e.g. Jackson and Schmugge, 1991). Using multifrequency, multipolarization radiometers it is possible to make simultaneous retrievals of several parameters provided that the number of independent measurement channels exceeds the number of parameters to be estimated. Such an approach may be applied in the future to data from EOS microwave sensors, and can be tested retrospectively

using data from the Scanning Multichannel Microwave Radiometer (e.g. Kerr and Njoku, 1990; van de Griend and Owe, 1994).

Two L-band (frequency~1.4 GHz or wavelength~21 cm) airborne radiometers have enabled several successful investigations of field soil moisture in recent years. The first is the pushbroom microwave radiometer (PBMR), which has been deployed in MACHYDRO'90 over the Mahantango Creek in Pennsylvania (Jackson et al., 1994) and in MONSOON'90 over the Walnut Gulch Watershed in Arizona (Goodrich et al., 1994; Jackson et al., 1993; Schmugge et al., 1994). The PBMR employs a real aperture antenna; the size of the antenna, if designed for a space-borne mission, is a major cost-driver. In contrast, the Electronically Scanned Thinned Array Radiometer (ESTAR), with its innovative use of aperture synthesis, offers encouraging prospects (Swift et al., 1991).

The concept of aperture synthesis was advanced in the field of radio astronomy as a means to achieve the finest resolving power with an antenna array that uses a relatively small number of individual elements. Because of the phase fidelity offered by microwave components, antenna complexity can be transformed to complexity in signal processing to obtain resolution which would not otherwise be achieved. Indeed, radio telescopes utilizing aperture synthesis and very long baseline interferometry rival and even exceed resolution achieved by some of the best earth-base optical telescopes.

Shown in Figure D4 is a simple block diagram of an airborne prototype of ESTAR; the current version is a hybrid, using real (stick) antennas to obtain resolution along track and aperture synthesis (between pairs of sticks) to obtain resolution across track (LeVine et al., 1990).

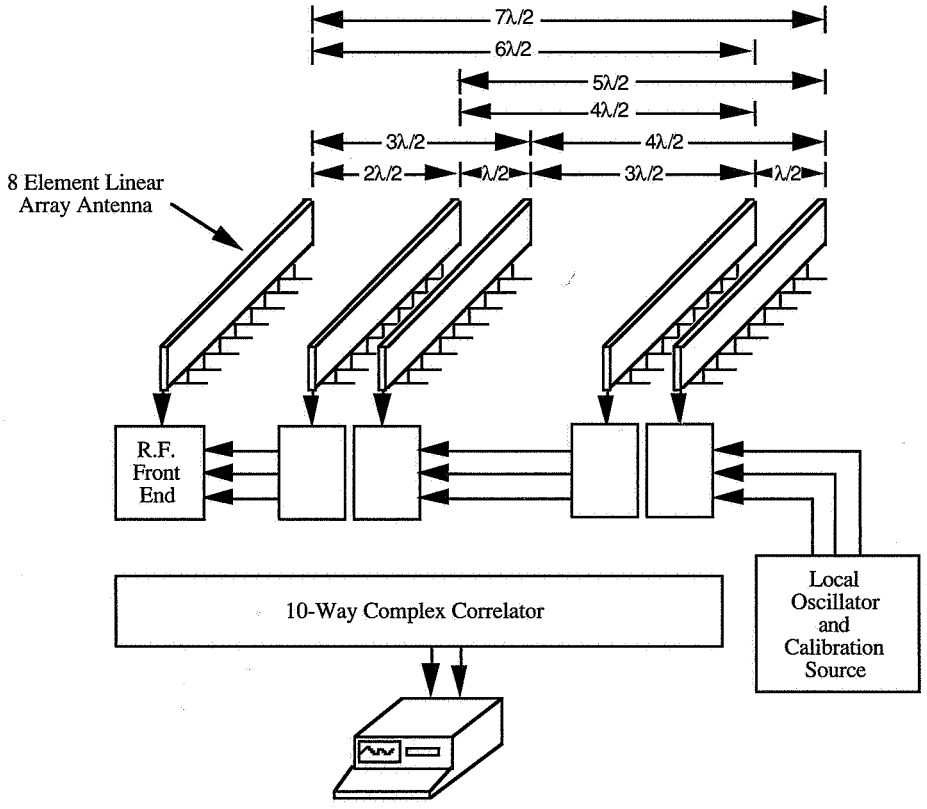


Figure D4. Example of thinned array antenna with five elements performing as a filled array of light elements (from Swift et al., 1991).

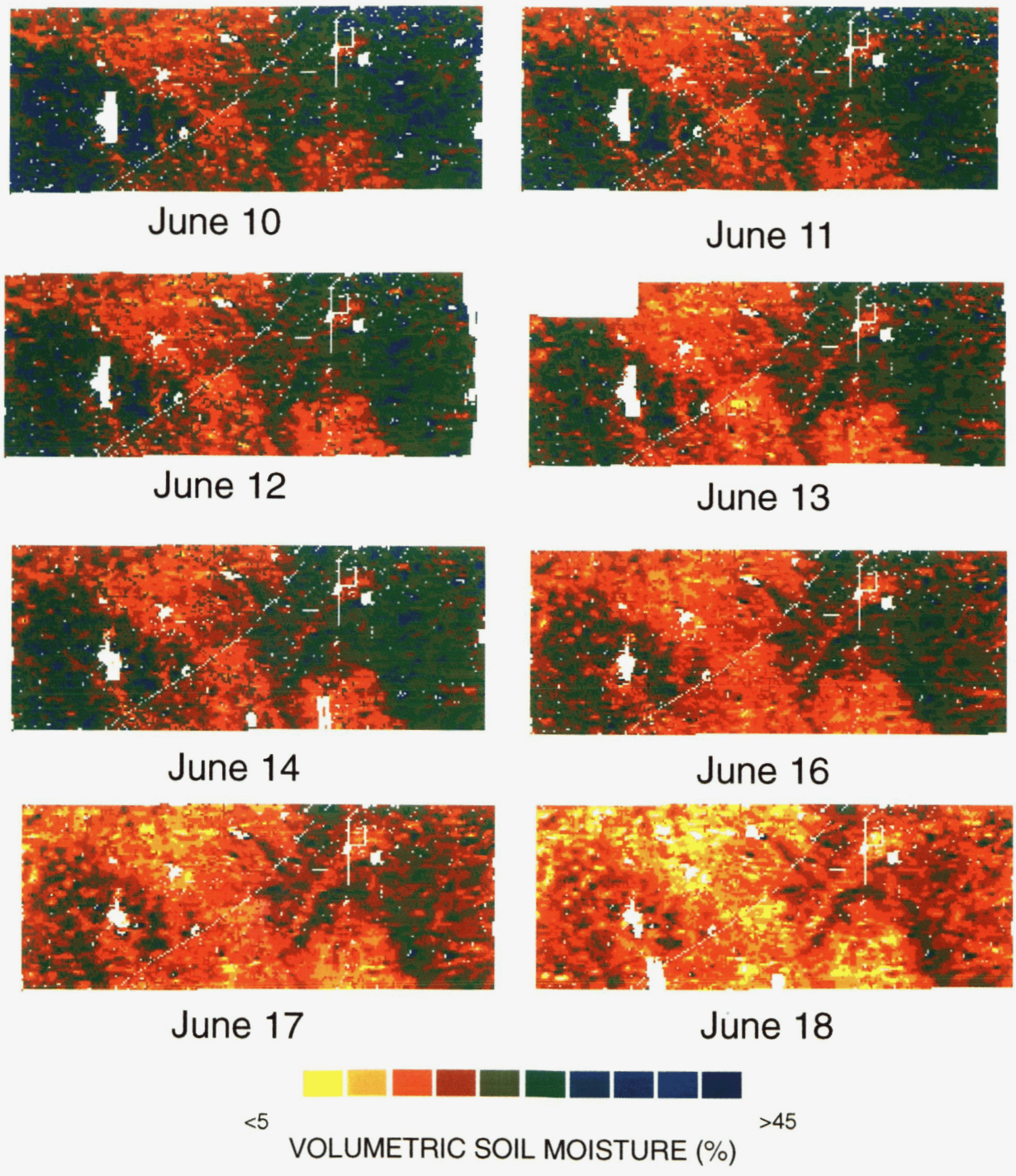


Figure 2. Washita'92 0-5 cm volumetric soil moisture images estimated with ESTAR (from Jackson et al., 1995); the dimensions are approximately 18 km by 45 km.

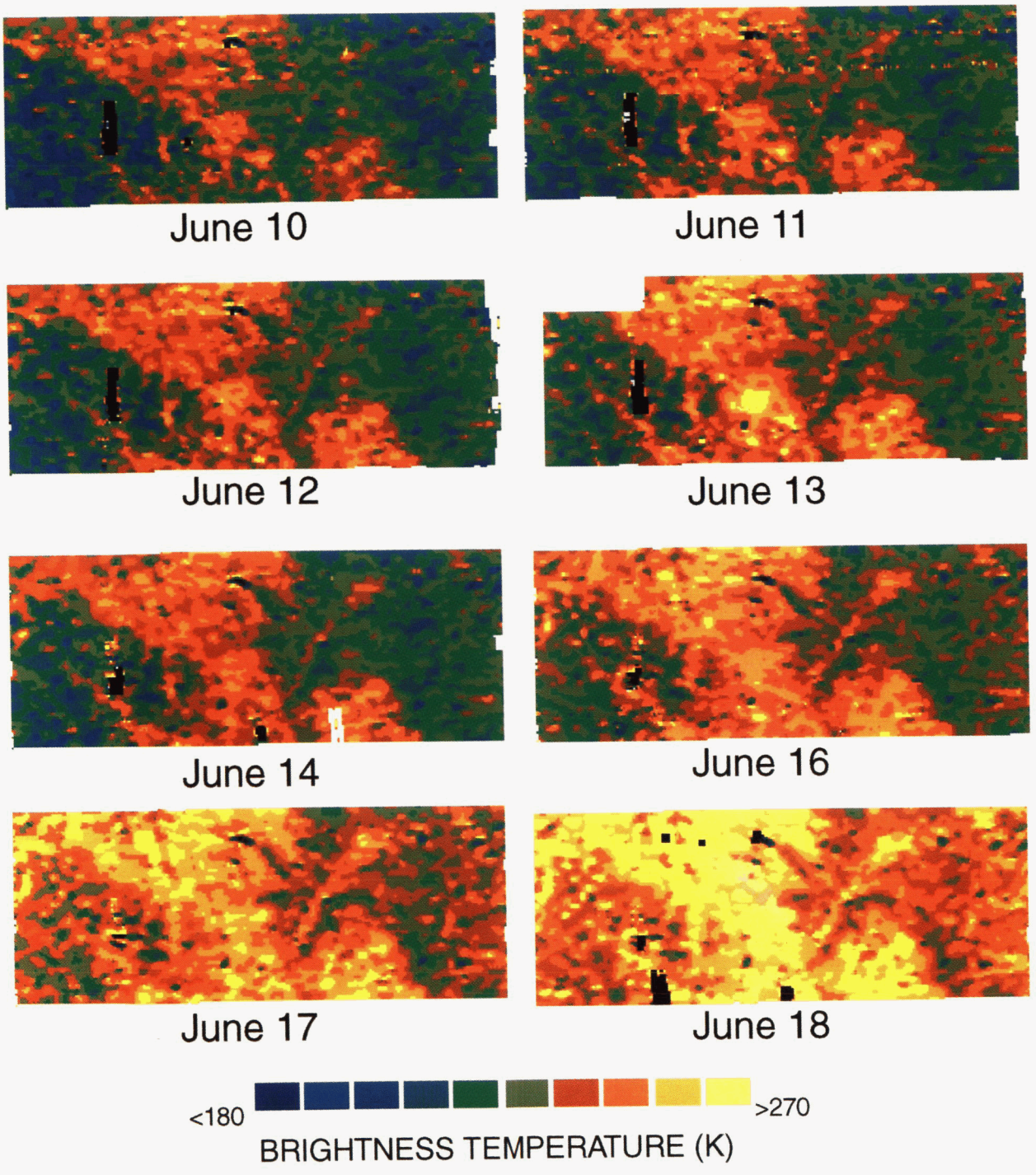


Figure D5. Washita'92 brightness temperature images at 200 m resolution (from Jackson et al., 1995).

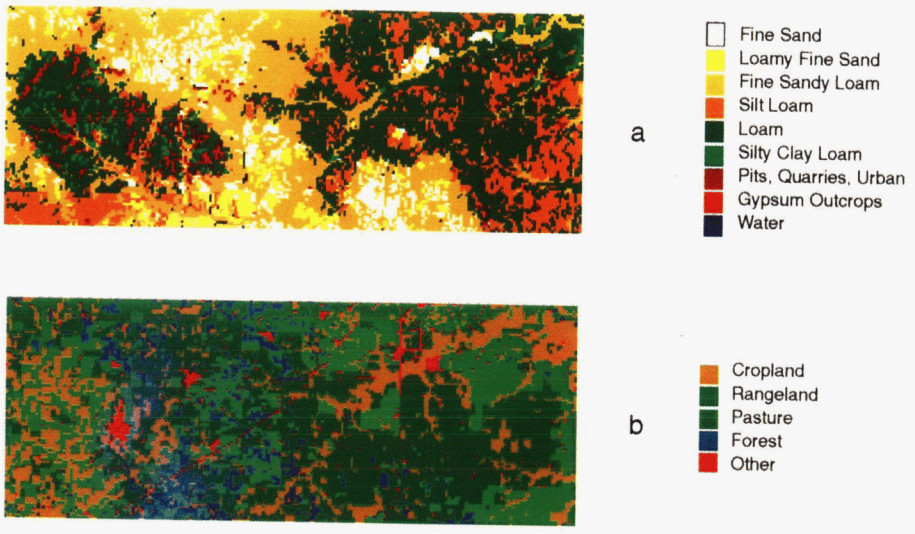


Figure D6. a) Soil texture and b) land cover from a geographic information system (GIS) for the Little Washita at 200 m resolution (from Jackson et al., 1995).

The nominal specifications of the instrument are:

Center frequency	1.4 GHz
Polarization	horizontal
Resolution	±8 degrees at nadir
Swath width	±45 degrees
Bandwidth	25 MHz
Integration time	0.25 seconds

The calibration of the ESTAR airborne instrument is achieved by viewing two scenes of known brightness temperatures. By plotting the measured brightness temperature against the theoretical response, a linear regression is developed for correction of gain and biases. Scenes used for calibration before and after a flight include blackbodies, sky, and water. With calibrated and geolocated brightness temperatures, an image can then be reconstructed with adjustments to incidence angles, temporal span of a particular flight, and gridding.

Shown in Figure D5 (page 39) are brightness temperature images of the Little Washita Watershed in Oklahoma during 10-18 June 1992 (Jackson et al., 1995). Prior to this period, the soil was saturated with standing water at some places; no additional rainfall was received during the experimental period, thus allowing the observation of surface drying (owing to either drainage or evaporative processes) over a substantial area. When juxtaposed with maps of soil texture and land cover (Figure D6; page 40), the spatial patterns of drying in Figure D5 appear to approximate the pattern of soil texture. Hydrologic fluxes and scaling properties are being analyzed; the ESTAR results from Washita'92 are clearly encouraging.

Active techniques

The imaging radar configuration most commonly used today is the synthetic aperture radar (SAR) which transmits a series of pulses as the radar antenna moves across the images scene; these pulses are then processed together to simulate a very long aperture capable of very high angular resolution along the direction of flight. The frequency range generally considered for soil moisture sensing is 0.4-10 GHz. The recent continuous observation of certain geographical regions by the C-band SAR aboard the European Space Agency (ESA) ERS-1 satellite has allowed empirical analysis of the data for estimating surface soil moisture (e.g., Cognard et al., 1995). However, SAR systems with multiple frequencies and polarizations are desirable owing to the increased amount of information extractable from radar images.

In general, microwave backscatter from natural surfaces is governed by three major factors: 1) the roughness statistics of the soil surface, 2) the soil moisture content, and 3) the vegetation covering the soil; thus,

$$\sigma^\circ = T^2\sigma^\circ_s + \sigma^\circ_{dv} + \sigma^\circ_{int}$$

where σ°_s is the backscatter contribution of the bare soil surface, T^2 is the two-way attenuation of the vegetation layer, σ°_{dv} is the direct backscatter contribution of the vegetation layer, and σ°_{int} represents multiple scattering involving the vegetation elements and the ground surface

① Direct Backscattering from Plants

② Direct Backscattering from Soil (Includes Two-Way Attenuation by Canopy)

③ Plant/Soil Multiple Scattering

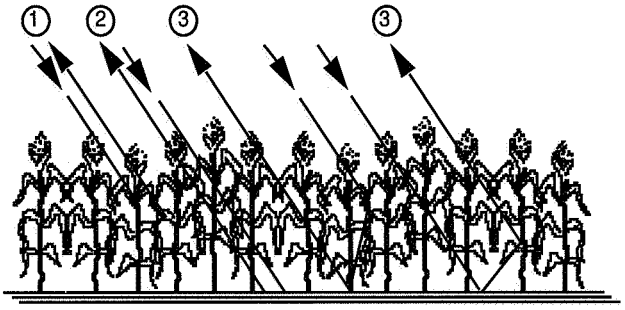


Figure D7. Backscattering contributions of a canopy over a soil surface.

(Figure D7). The "direct problem" in radar research seeks to predict the sensor response given adequate information about an imaged scene; once such models are developed, the "inverse problem" becomes possible allowing estimates of soil moisture and vegetation parameter from radar backscatter observations. If the models in the direct problem are mathematically simple in structure, the inverse solution is easy to derive; if the models are complex or very non-linear in structure, other approaches, such as neural networks, can be used to realize the inversion algorithm.

Presently the soil moisture inversion algorithms for vegetation-covered surfaces do not exist; however, the idea has been demonstrated with bare soil (Oh et al., 1992). Shown in Figure D8 is a schematic diagram showing the simultaneous solution for volumetric soil moisture content and *rms* height of the surface using ratios of radar cross-section HH/VV and HV/VV. Note that, if biomass is to be retrieved simultaneously with soil moisture and surface roughness, a multiple frequency polarimetric radar is essential, comprised of L-band and either C-band, X-band, or both.

The Shuttle Imaging Radar-C (SIR-C), consisting two polarimetric SARs operating at L-band (23.5 cm wavelength) and C-band (5.8 cm), and X-SAR, a single polarization SAR at 3.1 cm, were successfully flown in April and October 1994 (Stofan et al., 1995). The orbital altitude was 225 km. The resolution was 30 m × 30 m; the swath width ranged 15 to 90 km for the L-band and C-band, and 15 to 40 km for the X-band. A preliminary analysis of the data for surface soil moisture can be found in Dubois et al. (1995).

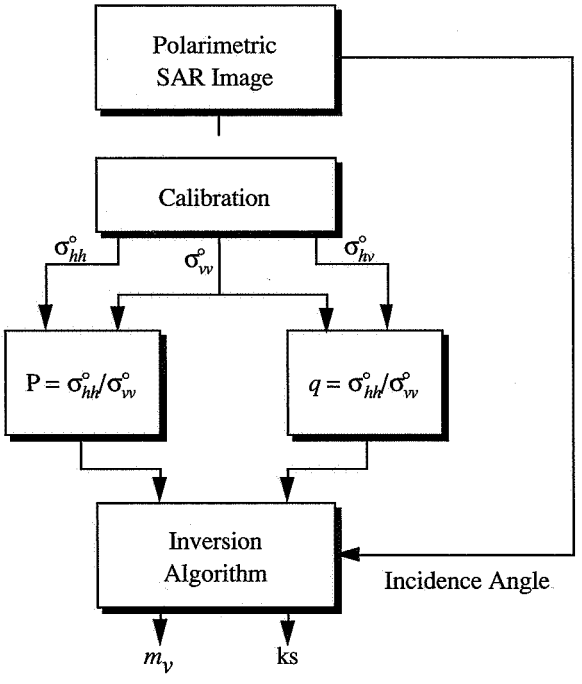


Figure D8. Schematic diagram for retrieving volumetric soil moisture content (m_v) and rms height of the surface from ratios of radar cross-sections (from Oh et al., 1992).

Appendix E. List of Long-term Soil Moisture Observations in the U.S. and Canada

Long-term measurement programs of soil moisture and thermal temperature are few in the U.S. and abroad. Listed below are a few known programs in North America.

1. Soil Conservation Service (SCS) soil moisture study 1979-1984

The SCS soil moisture study which began in 1979 was designed to provide input data to a soil moisture prediction system intended to help farm managers to utilize soil moisture reserves in production planning and crop selection to minimize wind erosion. A total of 66 sites in six major land resource areas were instrumented for operation which continued for at least 5 years. The location of the selected land resource areas and the number of sites for each are:

(1) Colorado - Central Great Plains
G-67 Central High Plains - wheat, fallow, grass
12 sites

(2) Georgia - Southeast
P-133 Southern Coastal Plain - corn, cotton, soybeans, grass
9 sites

(3) Indiana - East Corn Belt
M-111 Indiana and Ohio Till Plain - corn, soybeans, wheat, grass
16 sites

(4) North Dakota - Northern Great Plains
F-53 Dark Brown Glaciated Plain - wheat, small grain, fallow, grass
12 sites

(5) Texas - High Plains
H-77 Southern High Plains - cotton, wheat, grain sorghum, soybeans, grass
5 sites

(6) Washington - Palouse
B-8 Columbia Plateau - winter wheat, fallow, grass
12 sites

The sites were selected to represent local soil types and each of the major crop-soil-slope combination. Each site is 10 m by 10 m; four 5-cm electrical conduit access tubes were installed to a depth of 1/2 m or a restrictive rock layer at the corners of an 8 m by 8 m square centered within the site. Neutron probe was the primary instrument, though gravimetric measurements were also made at shallow locations. For the first two years, soil moisture measurements were made at approximately weekly intervals on all four tubes as long as the ground was not frozen; subsequently, the readings were made of two tubes per site at two-week intervals.

2. Illinois Climate Network

Established in 1981, the Illinois Climate Network provides timely meteorological and hydrologic information for agriculture, surface water management, and regional climate studies. The network includes 17 sites of soil water measurement across the State of Illinois (15 sites during 1983-1985); each site is equipped with the Troxler neutron probes which contain a depth probe as well as a surface probe. Measurements are made at 10 cm from the surface and subsequent depths at 20-cm intervals up to 1.9 m and the next 10 cm. From March to September, two readings are taken per month ; for the rest of the year, only one reading per month. Calibration with soil core samples has been performed at each site during the summer of 1988 (dry) and the spring of 1989 (wet). Further details can be found in Hollinger and Isard (1994).

3. Nevada Soil Climate Study

A cooperative study by the Nevada Agricultural Experiment Station at the University of Nevada, Reno, the Nevada Soil Conservation Service, and the Nevada Bureau of Land Management took place in 1983-1989. Transects of various soil moisture-temperature regimes were obtained. The soil moisture was measured using gypsum blocks to determine moist versus dry conditions; the measurements were made at 10-cm intervals to the depth of 1 m.

4. SCS Global Climate Change Pilot Project

Commencing in 1991, 21 pilot stations have been established throughout out the U.S. (Figure E1) for monitoring precipitation, surface air temperature and humidity, wind speed, solar radiation, and soil temperature and moisture. The soil temperature is measured by a thermistor sensor and the soil moisture, two thermistor sensors (Coleman and Watermark), at depths of 2, 4, 6, 8, 20, 40 and 80 inches. The data is stored in data pods at each site and transmitted to the SCS Database/Access Facility in Portland, Oregon. At this writing, the data is being analyzed to address the issue of calibration.

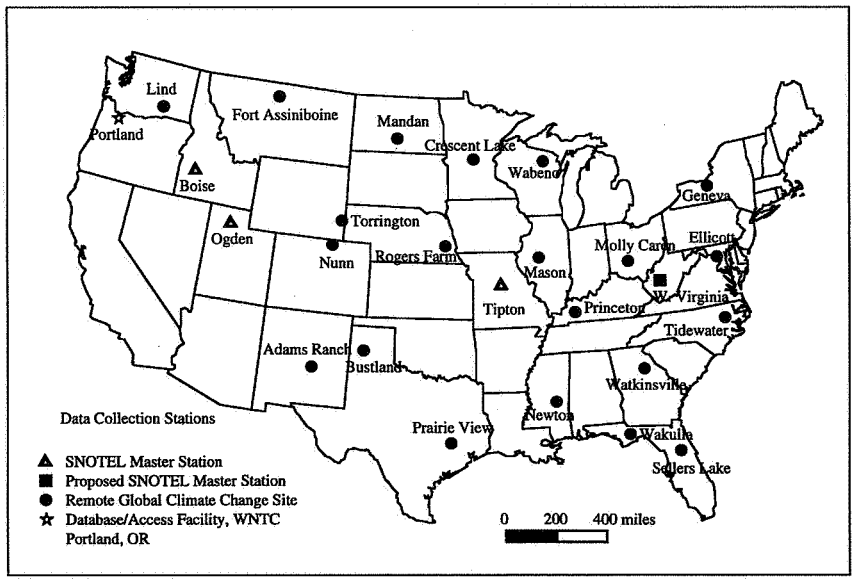


Figure E1. Soil moisture measurement sites for the Global Climate Change Pilot Project of the U.S. Department of Agriculture.

5. Canadian Prairie Soil Moisture Data

Listed below are some of the long-term soil moisture observations over the Canadian Prairies (Ripley, 1992); most are single-station data collected at Agriculture Canada Research Stations.

Source	Location	Time series	Depth	(*)
Manitoba Natural Resources	S. Man.; SE Sask.	November 1955-90	75 cm	(4)
Swift Current CDA	Swift Current	April-Oct. (5) 1967-90	120 cm	(5)
Lethbridge CDA	Lethbridge	Spring & Fall 1968-87	120 cm	(4)
Lacombe CDA	Lacombe	(1) 1979-83		(2)
		May-Sept. (13) 1984-86		(1)
		Spring 1985-87		(5)
Alberta Agriculture	All of Alberta	Fall 1982-90		(1)
		Spring 1988-90		(1)
Saskatchewan Inst. Pedology	All of Sask.	Nov. 1978-89		(1)

* Number of intervals

Appendix F. Soil Water and Solute transport Equations

The flow of water in the soil can be described microscopically and macroscopically. On the microscopic scale, the flow in each individual pore is considered; for each defined continuous pore, the Navier-Stokes equations apply. For their solutions, we lack detailed knowledge of the geometrical characteristics of individual pores to solve for a representative elementary volume (REV). Even with this knowledge, voluminous calculations would be required for even a relatively small soil domain.

The macroscopic or phenomenological approach of water transport considers the entire cross section of the soil when the condition of an REV is satisfied. The rate of water transport through the cross section of the REV is the flux. In order to emphasize the fact that water does not flow through the entire macroscopic areal cross section, the term flux density is used to describe the flow realized through only that portion of the area not occupied by the solid phase for water-saturated soils and not occupied by both the water and air phases for unsaturated soils. We use the term flux density to mean the volumetric water flux density having the dimensions of velocity [LT^{-1}].

Inasmuch as the principal equation derived for this macroscopic approach is Darcy's equation, the scale for which this approach is valid is often denoted as the Darcian scale. For soils, the area of this scale is usually in the range of cm^2 to m^2. Beyond this scale in either direction, larger or smaller, Darcian scale equations may not be realistic. On the Darcian scale, water flow in soils is comparable to other transport processes such as heat flow, molecular diffusion, etc. when the appropriate driving force is defined. Soil water flow is conditioned by the existence of a driving force stemming from a difference of total potentials between two points in the soil.

Basic equations usually begin with the simplest case of water flow in a water-saturated, homogeneous, inert, rigid soil at a constant temperature. Although the water flowing through the soil is actually a solution (and sometimes a mixture or suspension), it is generally assumed to be a homogeneous fluid with constant physical properties. Such water flow in a soil, not fully saturated with water, is commonly called unsaturated flow with the kinetics of the air phase usually neglected. If the flow of both air and water in the soil system is simultaneously considered, we speak of two-phase flow. In most derivations, it is assumed that the concentrations of the soil solution and the soil air do not affect soil water flow. Derivations are sometimes extended to swelling and shrinking soils that include changes in solid mass per bulk volume of soil as well as accompanying changes in pore size distributions for isothermal conditions. Linked or coupled flows of water and soil solutes are generally described for soils that do not swell and shrink. Physically, the flow of water in an unsaturated soil is always coupled with those of heat and solute even for isothermal conditions; however, for non-isothermal, unsaturated conditions, theoretical formulations and experimental observations for water transport have generally not included solute movement. The equations that include solute behavior remain in the developmental stage owing to a dearth of experimental observations and the lack of knowledge about parameters descriptive of the interfacial chemico-physical processes occurring within soil pores. A technology for water flow in unsaturated soils containing nonaqueous liquids remains immature and awaits further development.

For the majority of formulations, all components of the total potential except those of gravity and soil water are neglected. Hence, Darcy's equation is usually written as

$$q = -K(h)\,grad\,H \tag{1}$$

where q is the flux density of soil water [LT^{-1}], K the hydraulic conductivity [LT^{-1}], H the total potential head [L] comprised of the sum of the soil water potential head h and z the vertical coordinate. The unsaturated hydraulic conductivity K is physically dependent upon the soil water content θ because water flow is realized primarily in pores filled with water. Because the relationship $\theta(h)$ is strongly influenced by hysteresis, $K(h)$ is strongly hysteretic. On the other hand, $K(\theta)$ is only mildly hysteretic.

Inserting (1) into the equation of continuity, we have

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K(h)\frac{\partial H}{\partial x}\right] + \frac{\partial}{\partial y}\left[K(h)\frac{\partial H}{\partial y}\right] + \frac{\partial}{\partial z}\left[K(h)\frac{\partial H}{\partial z}\right] \tag{2}$$

provided that the soil is isotropic. In one-dimensional form for $H = h + z$ the above equation becomes

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K}{\partial z}. \tag{3}$$

Equations (2) and (3) are called Richards equations in the name of the author who first derived them in 1931.

If the soil is either wetting or drying, θ will be uniquely dependent upon only h and

$$\frac{\partial\theta}{\partial t} = \frac{d\theta}{dh}\frac{\partial h}{\partial t}. \tag{4}$$

Hence, the capacitance form of Richards equation is

$$C_W(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\frac{\partial h}{\partial z}\right] + \frac{\partial K}{\partial z} \tag{5}$$

where soil water capacity $C_W = \mathrm{d}\theta/\mathrm{d}h$ [L^{-1}]. An alternative derivation using

$$\frac{\partial h}{\partial z} = \frac{dh}{d\theta}\frac{\partial\theta}{\partial z} \tag{6}$$

leads to the diffusivity form of Richards equation

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right] + \frac{\mathrm{d}K}{\mathrm{d}\theta}\frac{\partial\theta}{\partial z} \tag{7}$$

where Darcy's equation has the diffusivity form

$$q = -D(\theta)\frac{\partial\theta}{\partial z} - K(\theta) \tag{8}$$

and the soil water diffusivity D is the term derived from

$$D(\theta) = K(\theta)\frac{dh}{d\theta}. \tag{9}$$

The main reason for the derivation of either the capacitance equation (5) or the diffusivity equation (7) is the reduction of the number of dependent variables from 2 to 1.

Both equations (5) and (7), strongly non-linear owing to functions $C_W(h)$, $K(h)$ and $D(\theta)$, are sometimes called Fokker-Planck equations. The name of (7) was derived from its resemblance (when its second term on the right hand side is omitted) to that for molecular diffusion. The units of D in (7) are identical to those of the diffusion coefficient.

The soil water diffusivity D has no direct physical meaning and is only defined mathematically. Moreover, inasmuch as $D(\theta)$ is dependent upon the derivative of the soil water retention curve $\theta(h)$, it has different values for wetting and drying processes. The temperature dependence of $D(\theta)$ is in general accordance with changes of surface tension and viscosity with temperature T. However, its prediction is only approximate owing to some not well understood phenomena relating to the temperature dependence of $h(\theta)$ and $K(\theta)$.

Owing to different dependence on temperature gradient, separate terms are required to describe the fluxes of liquid and vapor. Here, a slightly modified procedure of Philip and de Vries (1957) is used to describe the coupled flows. For the flux density of water vapor q_G we have

$$q_G = - D_{G\theta} \nabla\theta - D_{GT} \nabla T . \tag{10}$$

The dimension of D_{GT} is $[L^2T^{-1}grad^{-1}]$. For the flux density of liquid water q_L is

$$q_L = - D_{L\theta} \nabla\theta - D_{LT} \nabla T - K . \tag{11}$$

The dimension of D_{LT} is identical to that of D_{GT}.

The flux density of all of the pore water, both liquid and vapor, is

$$q = - D_\theta \nabla\theta - D_{GT} \nabla T - D_{LT} \nabla T - K \tag{12}$$

where $D_\theta = (D_{L\theta} + D_{G\theta})$ and $D_{G\theta}$ is the diffusivity of water vapor in the gaseous phase analogous to the earlier introduced soil water diffusivity

$$D_{G\theta} = D_p \frac{d\rho_{rG}}{d\theta} \tag{13}$$

where ρ_{rG} is the relative density (concentration) of water vapor and D_p the diffusion coefficient of water vapor in soil. Combining (12) with the equation of continuity for a one-dimensional, vertical system, we obtain

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial z}\left(D_\theta \frac{\partial\theta}{\partial z}\right) + \frac{\partial}{\partial z}\left(D_{GT} \frac{\partial T}{\partial z}\right) + \frac{\partial}{\partial z}\left(D_{LT} \frac{\partial T}{\partial z}\right) + \frac{\partial K}{\partial z} . \tag{14}$$

The temperature is described by

$$C_T \frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda_T \frac{\partial T}{\partial z}\right) + \rho_G \chi \frac{\partial}{\partial z}\left(D_{GT} \frac{\partial T}{\partial z}\right) \tag{15}$$

where λ_T is the thermal conductivity $[W \cdot m^{-1} \cdot K^{-1}]$, χ the latent heat of vaporization $[J \cdot kg^{-1}]$ and C_T the volumetric heat capacity $[J \cdot K^{-1} \cdot m^{-3}]$.

When a plant is rooted in a soil, evaporation E from the soil surface is accompanied by evaporation from the plant, which is commonly denoted as transpiration T_R. Water for transpiration is extracted from the soil by the root system. Macroscopically, we do not describe the influx of water into individual roots, but consider the flux averaged over a representative

volume of roots as we did with the flux of water in soil without roots. Here we use the macroscopic description of soil water extraction by the root system as a partner in the Darcian formulation of soil water flow. Therefore, (3) or other formulations of Richards equation is complemented by the extraction term S

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\frac{\partial H}{\partial z}\right] - S(z,t). \tag{16}$$

The change of soil water content θ in time t is now caused by the change of flux q as well as the extraction of water by roots on the scale of the REV. The dimension of S is $[L^3L^{-3}T^{-1}]$ or, simply $[T^{-1}]$. Transpiration T_R is given by

$$T_R = \int_0^Z \int_0^t S(z,t)\,dt\,dz \tag{17}$$

where Z is the depth of the root zone.

Two different kinds of extraction terms S can be grouped together. In the first group, the value of potential transpiration is related to the maximum value of soil water extraction S_{max} by roots extending within the profile to a root zone depth z_r by $T_{RP}/z_r = S_{max}$. This relation is usually defined by some deterministic function of root length or related plant parameter. Inasmuch as S_{max} depends upon the development of the root system, it is appropriate to describe $S_{max}(z, t)$.

In the second group, the resistance to water flow is considered at the soil-root interface or within the roots. The water flux in the plant is computed and related to T_{RP} by an iterative procedure. Inasmuch as direct measurement of resistances of plant water flow and xylem water potentials is difficult, plant hydraulic characteristics are frequently obtained from values of plant parameters adjusted to match directly measured or computed T_{RP}.

In general, soil solutes exist in both gaseous and aqueous phases and are related to the solid organic and inorganic phases of the soil. Moreover, nonaqueous polar and nonpolar liquids can also reside in soils and participate in soil transport processes. Here, we neglect nonaqueous polar and nonpolar liquids and assume that some solutes in the soil solution are sufficiently volatile to consider their content or transport in the gaseous phase. Hence, the total solute concentration S is

$$S = \rho_T C_S + \theta C + (P - \theta) C_G \tag{18}$$

where ρ_T is the soil bulk density [M L^{-3}], C_S the solute adsorbed or exchanged on the soil solids [M (M of dry soil)$^{-1}$], θ the volumetric soil water content, and C the solute in solution [M L^{-3}], P the porosity and C_G the solute in the soil air [M L^{-3}].

The solute flux density J is difficult to define unambiguously owing to the fact that the representative elementary volumes of each of the terms in J and S are not necessarily equal nor known, particularly for structured field soils. Each of the directional components of J is comprised of contributions of solute movement within the gaseous and liquid phases as well as along particle surfaces of the solid phase. We assume that solute movement along soil particle surfaces is nil or can be accounted for by functions relating the concentration of solutes in solution to that associated with the solid phase. Hence, the solute flux density consists of three terms, one describing the bulk transport of the solute moving with the flowing soil solution, the second describing the solute moving by molecular diffusion and meandering convective paths within the soil solution and the third accounting for molecular diffusion in the gaseous phase.

Inasmuch as for simplicity, we ignore gaseous convection which indeed exists during changes in soil water content. For the z-direction, we have

$$J_z = q_z C - \theta\left(D_{c_z} + D_{m_z}\right)\frac{\partial C}{\partial z} - (P-\theta)D_G\frac{\partial C_G}{\partial z} \qquad (19)$$

where q_z is the Darcian flux, D_{c_z} and D_{m_z} are the coefficients of convective dispersion and molecular diffusion in the soil solution, respectively, D_G the molecular diffusion coefficient in the soil air and C_G the gaseous solute concentration in the soil air. We continue the analysis here for only the vertical soil profile direction z avoiding vectorial and tensorial notation.

Substituting (18) and (19) into the equation of continuity, we obtain for solute of the soil solution that does not volatilize into the soil air

$$\frac{\partial(\rho_T C_S)}{\partial t} + \frac{\partial(\theta C)}{\partial t} = \frac{\partial}{\partial z}\left[\theta\left(D_c + D_m\right)\frac{\partial C}{\partial z}\right] - \frac{\partial(qC)}{\partial z} + \sum_i \phi_i. \qquad (20)$$

The first term of (20) describes the rate at which a solute reacts or exchanges with the soil solids. Its exact form continues to be debated and both equilibrium and kinetic rate terms are commonly used to describe this adsorption-exchange process. The term D_a is frequently substituted for (D_c + D_m). The source-sink term ϕ_i is often approximated by zero- or first-order rate terms

$$\phi_i = \gamma\theta + \gamma_s\rho + \mu\theta C + \mu_s\rho_T C_s \qquad (21)$$

where γ and γ_s are rate constants for zero-order decay or production in the soil solution and solid phases, respectively, and μ and μ_s are similar first-order rate constants for the two phases. For radioactive decay, physicists assume that μ and μ_s are identical as well as that γ and γ_s are nil. Microbiologists, considering organic and inorganic transformations of soil solutes in relation to growth, maintenance and waste metabolism of soil microbes as a Michaelis-Menten process. Agronomic or plant scientists consider ϕ_i as an irreversible sink and source of solutes taking place in the vicinity of the rhizosphere of cultivated or uncultivated plants as a function of soil depth and time as well as some empirical function defining the root distribution.

Equation (20) is often sequentially repeated when organic or inorganic products are of interest, especially when the products form a consecutive chain of reactions (e. g., for nitrogen urea $\rightarrow NH_4^+ \rightarrow NO_3^- \rightarrow N_2$). In such cases, a set of simultaneous equations stemming from (20) becomes

$$\begin{aligned}
\frac{\partial(\rho_T C_{S1})}{\partial t} + \frac{\partial(\theta C_1)}{\partial t} &= \frac{\partial}{\partial z}\left(D_{a_1}\frac{\partial C_1}{\partial z}\right) - \frac{\partial(qC_1)}{\partial z} + \phi_1 \\
\frac{\partial(\rho_T C_{Sj})}{\partial t} + \frac{\partial(\theta C_j)}{\partial t} &= \frac{\partial}{\partial z}\left(D_{a_j}\frac{\partial C_j}{\partial z}\right) - \frac{\partial(qC_j)}{\partial z} - \phi_{j-1} + \phi_j
\end{aligned} \qquad (22)$$

where $j = 2, 3, \cdots n$, and n is the number of species considered in the reaction chain. The equations are linked to each other by their mutual ϕ_j terms. These equations have been applied to consecutive decay reactions of soil carbon, nitrogen and phosphorus species as well as those of a few selected organic compounds occurring naturally or added to the soil intentionally or unintentionally.

Although many other models are available, the most frequently used model of solute transport in soils is the formulation of Richards equation for unsaturated water flow coupled with convection-diffusion equations similar to (20) for solute transport. In addition to water flow, heat transport should be included because the temperature significantly influences thermodynamic constants and reaction rates. Moreover, the concentration of CO_2 in soil air fluctuates between 0.035% and 20% in extreme circumstances. The solubility of many mineral salts strongly depends upon CO_2 concentration. Changes in CO_2 concentration are accompanied by changes of O_2 concentration in the soil air. Both concentrations influence pH and there is a direct link between both pH and redox potential with dissolution constants and rates. Hence, multicomponent transport models are preferred to better approximate field reality.

Appendix G. Glossary of Technical Terms

Blackbody — An idealized, perfectly opaque material that absorbs all the incident radiation at all frequencies, reflecting none; also a perfect emitter.

Boundary layer conductance — The proportionality constant between the rate of leaf or canopy transpiration and the water vapor concentration gradient between a leaf or canopy surface and the air outside the leaf or canopy boundary layer.

Brightness temperature — A term used to represent the intensity of radiation emitted by the scene under observation; a function of physical temperature and emissivity.

Data assimilation — A process of incorporating observations of a dynamical system into its mathematical representation; based on estimation theory, it provides the best estimate of the state of the system and its evolution through a synthesis of theoretical and *a priori* knowledge with all available observational information.

Dielectric constant — A complex number representing the electric permittivity of a material; the real part is a measure of the energy stored by the dipoles aligned in an applied electromagnetic field, and the imaginary part a measure of energy dissipation rate in the medium. The dielectric constant of moist soil depends on the amount of water that is bound to the soil particles and that is free; free water has a higher dielectric constant than bound water.

Emissivity — The ratio of the radiant energy of a certain wavelength at a certain temperature and the radiant energy of a blackbody of the same wavelength and at the same temperature; a blackbody has an emissivity of one.

Evapotranspiration — The combined evaporation from the soil surface and transpiration from plants.

Exfiltration — Ascension of water from saturated zone by capillarity into the unsaturated zone and further dissipation at the ground surface by diffusion; converse of infiltration.

Hydraulic lift — Upward movement of water through plant roots from deeper, moister layers in the soil to shallower, drier layers.

Infiltration	Flow of water through soil surface into underground.
Interflow	Prompt subsurface flow through pipes, macropores and seepage zones in the soil; lateral subsurface runoff.
Net primary production	The biomass or biocontent incorporated into a plant community during a specified period of time.
Ped	An individual, natural aggregate of soil particles.
Pedon	The smallest vertical column of soil containing all the soil horizons present at that point.
Pedotransfer function	Relation between dynamic soil variables and static soil characteristics; usually between soil hydraulic properties (unsaturated hydraulic conductivity function or water retention function) and descriptive data about the soil (e.g., particle size distribution, bulk density, organic matter, pore space, etc.).
Percolation	Flow of water through intergranular and fissured flow spaces under saturated and laminar conditions under a hydraulic gradient.
Primary production	The total quantity of organic matter newly formed by photosynthesis.
Redox potential	Oxidation-reduction potential.
Stomatal conductance	The proportionality constant between the rate of leaf transpiration and the water vapor concentration gradient between a leaf's interior and the air outside the leaf.

Appendix H. Additional References Regarding Soil Moisture

Hydrology and Remote Sensing

Ahuja, L. R., O. Wendroth, and D. R. Nielson, Relationship between the initial drainage of surface soil and average profile saturated hydraulic conductivity, *Soil Sci. Soc. Am. J., 57,* 19–25, 1993.

Arya, L. M., J. C. Richter, and J. F. Paris, Estimating profile water storage from surface zone soil moisture measurements under bare field conditions, *Water Resour. Res., 19*(2), 403–412, 1983.

Beljaars, A. C. and A. A Holtslag, Flux parameterization over land surfaces for atmospheric models, *J. Appl. Meteor., 30,* 327–341, 1991.

Bernard, R., M. Vaculin, and D. Vidal-Madjar, Possible use of active microwave remote sensing data for prediction of regional evaporation by numerical simulation of soil water movement in the unsaturated zone, *Water Resour. Res., 17*(6), 1603–1610, 1981.

Bernard, R., J. V. Soares, and D. Vidal-Madjar, Differential bare field drainage properties from airborne microwave observations, *Water Resour. Res., 22*(6), 869–875, 1986.

Brutsaert, W., and M. Sugita, A bulk similarity approach in the atmosphere boundary-layer using radiometric skin temperature to determine regional surface fluxes, *Bound. Layer Meteor., 55,* 1–12, 1991.

Brutsaert, W., and M. Sugita, Regional surface fluxes from satellite-derived surface temperatures (AVHRR) and radiosonde profiles, *Bound. Layer Meteor., 58,* 355–366, 1992a.

Brutsaert, W., and M. Sugita, Regional surface fluxes under nonuniform soil moisture conditions during drying, *Water Resour. Res., 28,* 669–1674, 1992b.

Brutsaert, W., A. Hsu, and T. J. Schmugge, Parameterization of surface heat fluxes above forest with satellite thermal sensing and boundary layer sounding, *J. Appl. Meteor., 32,* 909–917, 1993.

Camillo, P. J., Using a one- or two-layer models for evaporation estimation with remotely sensed data, in *Land Surface Evaporation: Measurement and Parameterization,* edited by T. J. Schmugge and J. C. Andre, 183–197, Springer Verlag, New York, 1991.

Camillo, P., and T. J.Schmugge, Estimating soil moisture storage in the root zone from surface measurements, *Soil. Sci., 135*(4), 245–264, 1983.

Carlson, T. N., J. K. Dodd, S. G. Benjamin, and J. N. Cooper, Satellite estimation of the surface energy balance, moisture availability and thermal inertia, *J. App. Meteor., 20,* 67–87, 1981.

Carlson, T. N., E. M. Perry, and T. J. Schmugge, Remote estimation of soil moisture availability and fractional vegetation cover for agricultural fields, *Ag. and Forest Meteor., 52,* 45–69, 1990.

Choudhury, B. J., Monitoring global land surface using Nimbus-7 37 GHz data: Theory and observations, *Intl. J. Remote Sens., 10,* 1579–1605, 1989.

Choudhury, B. J., and R. E. Golus, Estimating soil wetness using satellite data, *Intl. J. Remote Sensing, 9,* 1251–1257, 1988.

Choudhury, B. J., T. J. Schmugge, R. W. Newton, and A. T. C. Chang, Effect of surface roughness on microwave emission of soils, *J. Geophys. Res., 84,* 5699–5706, 1979.

Choudhury, B. J., T. J. Schmugge, and T. Mo, A parameterization of effective temperature for microwave emission, *J. Geophys. Res., 87,* 1301–1304, 1982.

Coll, C., V. Caselles, and T. J. Schmugge, Estimation of land surface emissivity differences in the split-window channels of AVHRR, *Remote Sens. Environ.,*48(2), 127–134, 1994.

Dobson, M. C., F. T. Ulaby, M. T. Hallikainen, and M. A. El-Rayes, Microwave dielectric behavior of wet soil, Part II: Dielectric mixing models, *IEEE Trans. Geosci. Remote Sens., GE-23,* 35–46, 1985.

Dobson, M. C., and F. T. Ulaby, Preliminary evaluation of the SIR-B response to soil moisture, surface roughness and crop canopy cover, *IEEE Trans. Geosci. Remote Sens., GE-24,* 51–61, 1986.

England, A. W., J. F. Galantowicz, and M. S. Schretter, The radiobrightness thermal inertia measure of soil moisture, *IEEE Trans. Geosci. Remote Sens., 30*(1), 132–139, 1992.

Engman, E. T., G. Angus, W. P. Kustas, and J. R. Wang, Relationships between the hydrologic balance of a small watershed and remotely sensed soil moisture, *IAHS Publ., 186,* 76–84, 1989.

Flury, M., H. Fluhler, W. A. Jury, and J. Leuenberger, Susceptibility of soils to preferential flow of water: A field study, *Water Resour. Res., 30*(7), 1945-1954, 1994.

Goodrich, D. C., T. J. Schmugge, T. J., Jackson, D. L. Unkrich, T. O. Keefer, R. Parry, L. B. Bach, and S. A. Amer, Runoff simulation sensitivity to remotely sensed initial soil water content, *Water Resour. Res., 30*(5), 1393–1405, 1994.

Hall, F. G., K.F. Huemmerich, S. J. Goetz, P. J. Sellers, and J. E. Nickerson, Satellite remote sensing of surface energy balance: Success, failures and unresolved issues in FIFE, *J. Geophys. Res., 97,* 19,061–19,089, 1992.

Hatfield, J. L., R. J. Reginato, and S. B. Idso, Evaluation of canopy temperature-evapotranspiration models over various crops, *Ag. For. Meteorol., 32,* 41–53, 1984a.

Hatfield, J. L., M. Vauclin, S. R. Vieira, and R. Bernard, Surface temperature variability patterns within irrigated fields, *Ag. Water Mgmt., 8,* 429–437, 1984b.

Heymsfield, G. A., and R. Fulton, Modulation of SSM/I microwave soil radiances by rainfall. *Remote Sens. Environ., 29,* 187–202, 1992.

Hollinger, J. P., J. L. Peirce, and G. A. Poe, SSM/I instrument evaluation. *IEEE Trans. Geosci. Remote Sens., 28*(5), 781–790, 1990.

Humes, K. S., W. P. Kustas, M. S. Moran, W. D. Nichols, and M. A. Weltz, Variability in emissivity and surface temperature over a sparsely vegetated surface, *Water Resour. Res., 30,* 1299–1310, 1994.

Jackson, R. D., M. S. Moran, L. W. Gay, and L. H. Raymond, Evaluating evaporation from field crops using airborne radiometry and ground-based meteorological data, *Irrig. Sci., 8,* 81–90, 1987.

Jackson, T. J., Profile soil moisture from surface measurements, *J. Irrig. Drain. Div. ASCE, 106*(IR2), 81–92, 1980.

Jackson, T. J., Soil water modeling and remote sensing, *IEEE Trans. Geosci. Remote Sens., GE-24*(1), 37–46, 1986.

Jackson, T. J., Measuring surface soil moisture using passive microwave remote sensing, *Hydro. Proc., 7,* 139–152, 1993.

Jackson, T. J., and T. J. Schmugge, Passive microwave remote sensing system for soil moisture: Some supporting research, *IEEE Trans. Geosci. Remote Sens., GE-27,* 225–235, 1989.

Jackson, T. J., and T. J. Schmugge, Vegetation effects on the microwave emission of soils, *Remote Sens. Environ., 36,* 203–212, 1991.

Jackson, T. J., T. J. Schmugge, and P. E. O'Neill, Passive microwave remote sensing of soil moisture from an aircraft platform, *Remote Sens. Environ., 14,* 135–152, 1984.

Jackson, T. J., M. E. Hawley, and P.E. O'Neill, Preplanting soil moisture using passive microwave sensors, *Water Resour. Bull., 23,* 11–19, 1987.

Jackson, T. J., D. M. Le Vine, A. Griffis, D. C. Goodrich, T. J. Schmugge, C. T. Swift, and P. E. O'Neill, Soil moisture and rainfall estimation over a semiarid environment with the ESTAR microwave radiometer, *IEEE Trans. Geosci. Remote Sens., 31,* 836–841, 1993.

Kerr, Y., J. P. Lagouarde, and J. Imbernon, Accurate land surface temperature retrieval from AVHRR data with the use of an improved split window algorithm, *Remote Sens. Environ., 41,* 197–209, 1992.

Kirdiashev, K. P., A. A. Chukhlantsev, and A. M. Shutko, Microwave radiation of the Earth's surface in the presence of vegetation, *Radio Eng. and Elec., 24,* 256–264, 1979.

Kondratyev, K. Y., V. V. Melentyev, Y. I. Rabinovich, and E. M. Shulinga, Passive microwave remote sensing for soil moisture, *Proceed. 11th Symp. Remote Sensing Environment,* 1977.

Kostov, K. G. and T. J. Jackson, Estimating profile soil moisture from surface layer measurements—A review, *Proceed. SPIE Symp. Aerospace Remote Sensing,* 125–136, 1993.

Kustas, W. P., B. J. Choudhury, M. S. Moran, R. J. Reginato, R. D. Jackson, L. W. Gay, and H. L. Weaver, Determination of sensible heat flux over sparse canopy using thermal infrared data, *Ag. For. Meteorol., 44,* 197–216, 1989.

Kustas, W. P., M. S. Moran, R. D. Jackson, L. W. Gay, L. F. Duell, K. E. Kunkel, and A. D. Matthias, Instantaneous and daily values of the surface energy balance over agricultural fields using remote sensing and a reference field in an arid environment, *Remote Sens. Environ., 32,* 125–141, 1990a.

Kustas, W. P., T. J. Schmugge, K. S. Humes, M. A. Weltz, M. S. Moran, T. J. Jackson, and R. Parry, Relationships between evaporative fraction and remotely sensed vegetation index and microwave brightness temperature for semiarid rangelands, *J. Appl. Meteor., 32,* 1781–1790, 1993.

Lin, D. S., E. F. Wood, P. A. Troch, M. Mancini, and T. J. Jackson, Comparisons of remotely sensed and model simulated soil moisture over a heterogeneous watershed, *Remote Sens. Environ., 48,* 159-171, 1994.

Nemani, R. R., L. Pierce, S. Running, and S. Goward, Developing satellite-derived estimates of surface moisture status, *J. Appl. Meteor., 32,* 548–557, 1993.

Njoku, E. G., and J. A. Kong, Theory for passive microwave remote sensing of near-surface soil moisture, *J. Geophys. Res., 82*(20), 3108–3118, 1977.

Owe, M., A. A. van de Griend, and A. T. C. Chang, Surface soil moisture and satellite microwave observations in semiarid southern Africa, *Water Resour. Res., 28*(3), 829–839, 1992.

Prevot, L., R. Bernard, O. Taconet, and D. Vidal-Madjar, Evaporation from a bare soil evaluated using a soil water transfer model and remotely sensed surface soil moisture data, *Water Resour. Res., 20*(2), 311–316, 1984.

Rawls, W. J., T. J. Gish, and D. L. Brakensiek, Estimation of soil water retention from soil properties—A review, *Advan. Soil Sci., 16,* 213–235, 1991.

Reginato, R. J., R. D. Jackson, and P. J. Pinter, Evaporation calculated from remote multispectral and ground station meteorological data, *Remote Sens. Environ., 19,* 75–89, 1985.

Reutov, E. A., and A. M. Shutko, Prior-knowledge-based soil moisture determination by microwave radiometry, *Soviet J. Remote Sens., 5*(1), 100–125, 1986.

Reutov, E. A., and A. M. Shutko, Microwave spectroradiometry of water content of nonuniformly moistened soil with a surface transition layer, *Soviet J. Remote Sens., 6*(1), 72–79, 1990.

Reutov, E. A., and A. M. Shutko, Estimation of the depth to a shallow water-table using microwave radiometry, *Intl. J. Remote Sens., 13,* 2223–2232, 1992.

Schmugge, T. J., T. J. Jackson, and H. L. McKim, Survey of methods for soil moisture determination, *Water Resour. Res., 16*(6), 961–979, 1980.

Schmugge, T. J., P. E. O'Neill, and J. R. Wang, J. R., Passive microwave soil moisture research, *IEEE Trans. Geosci. Remote Sens., GE-24,* 12–22, 1986.

Schmugge, T. J., T. J. Jackson, W. R. Kustas, and J. R. Wang, Passive microwave remote sensing of soil moisture: Results from HAPEX, FIFE and MONSOON 90, *ISPRS J. Photo. Remote Sens., 47,* 127–143, 1992.

Schmugge, T. J., J. R. Wang, and G. Asrar, Results from the push broom microwave radiometer flights near the Konza Prairie in 1985, *IEEE Trans. Geosci. Remote Sens., 26,* 590–596, 1988.

Shutko, A. M., Remote sensing of the waters and lands via microwave radiometry (the principles of method, problems feasible for solving, economic use), *Pontificiae Academiae Scientiarvm Scripta Varia, 68,* 413–440, 1986.

Shuttleworth, W. J., and R. J. Gurney, The theoretical relationship between foliage temperature and canopy resistance in sparse crops, *Quart. J. Rev. Meteorol. Soc., 11,* 497–519, 1991.

Sugita, M., and W. Brutsaert, Regional surface fluxes from remotely sensed skin temperature and lower boundary layer measurements, *Water Resour. Res., 26,* 2937–2944, 1990.

Teng, W. L., J. R. Wang, and P. C. Doraiswamy, Relationship between satellite microwave radiometric data, antecedent precipitation index, and regional soil moisture, *Intl. J. Remote Sens., 14*(13), 2483–2500, 1993.

van Genuchten, M. T., F. J. Leij, and L. J. Lund (Eds.), *Indirect methods for estimating the hydraulic properties of unsaturated soils*, Univ. of California, Riverside, CA, 718 pp., 1992.

Wang, J. R. Effect of vegetation on soil moisture sensing from an orbiting radiometer, *Remote Sens. Environ., 17,* 141–151, 1985.

Wang, J. R., and T. J. Schmugge, An empirical model for the complex dielectric permittivity of soils as a function of water content, *IEEE Trans. Geosci. Remote Sens., GE-18,* 288–295, 1980.

Wang, J. R., E. T. Engman, J. C. Shiue, M. Rusek, M., and C. Steinmeier, The SIR-B observations of microwave backscatter dependence on soil moisture, surface roughness and vegetation covers, *IEEE Trans. Geosci. Remote Sens., GE-24*, 510–516, 1986.

Wang, J. R., J. C. Shuie, T. J. Schmugge, and E. T. Engman, Mapping surface soil moisture with L-band radiometric measurements, *Remote Sens. Environ., 27,* 305–312, 1989.

Wang, J. R., J. C. Shiue, T. J. Schmugge, and E. T. Engman, The L-band PBMR measurements of surface soil moisture in FIFE, *IEEE Trans. Geosci. Remote Sens., 28,* 906–914, 1990.

Wegmuller, U., C. Matzler, and E. Schanda, Microwave signatures of bare soil, *Adv. Space Res., 9,* 307–316, 1989.

Wilheit, T. T., Radiative transfer in a plane stratified dielectric, *IEEE Trans. Geosci. Remote Sens., GE-16,* 138–143, 1978.

Witono, H., and L. Bruckler, Use of remotely sensed soil moisture content as boundary conditions in soil-atmosphere water transport modeling: 1. Field validation of a water flow model, *Water Resour. Res., 25*(12), 2423–2435, 1989.

Wood, E. F., D. S. Lin, M. Mancini, D. Thongs, P. A. Troch, T. J. Jackson, J. S. Famiglietti, and E. T. Engman, Intercomparisons between passive and active microwave remote sensing and hydrological modeling for soil moisture, *Adv. Space Res., 13*(5), 5167-5176, 1993.

Wuthrich, M., ERS-1 SAR compared to thermal infrared to estimate surface soil moisture, *Proceed. AMS 21st Conf. Agriculture Forest Meteorology,* 197–200, San Diego, CA, March 7–10, 1994.

Soil Science

Addiscott, T. M., and R. J. Wagenet, Concepts of solute leaching in soils: A review of modeling approaches, *J. Soil Sci., 36,* 411–424, 1985.

Alemi, M. H., D. R. Nielsen, and J. W. Biggar, Determining the hydraulic conductivity of soil cores by centrifugation, *Soil Sci. Soc. Am. J., 40,* 212–218, 1976.

Amoozegar, A. , D. R. Nielsen, and A. W. Warrick, Soil solute concentration distributions for spatially varying pore water velocities and apparent diffusion coefficients, *Soil Sci. Soc. Am. J., 46,* 3–9, 1982.

Amoozegar, A., and A. W. Warrick, Field measurements of saturated hydraulic conductivity, in *Methods of Soil Analysis,* Part I, edited by A. Klute, Agronomy Monograph Series No. 9 (2nd ed.), p. 735–770, ASA and SSSA, Madison, Wisc., 1986.

Arya, L. M., and J. F. Paris, A physicoempirical model to predict the soil moisture characteristic from particle size distribution and bulk density data, *Soil Sci. Soc. Am. J., 45,* 1023–1030, 1981.

Bazin, M. J., P. T. Saunders, and J. I. Prosser, Models of microbial interactions in the soil, *Chemical Rubber Co. (CRC) Crit. Rev. Microbiol., 5,* 464–497, 1976.

Beven, K., and P. Germann, Macropores and water flow in soils, *Water Resour. Res., 18,* 1311–1325, 1982.

Biggar, J. W., and D. R. Nielsen, Spatial variability of the leaching characteristics of a field soil, *Water Resour. Res., 12,* 78–84, 1976.

Binley, A., K. Beven, and J. Elgy, A physically based model of heterogeneous hillslopes: 2. Effective hydraulic conductivities, *Water Resour. Res., 25,* 1227–1233, 1989.

Binley, A., J. Elgy, and K. Beven, A physically based model of heterogeneous hillslopes: 1. Runoff production, *Water Resour. Res., 25,* 1219–1226, 1989.

Bolt, G. H., and P. H. Groenevelt, Coupling between transport processes in porous media, *Proceed. 2nd Symp. Fundamentals Transport Phenomena in Porous Media,* 630–652, Univ. of Guelph, Guelph, Ont., 1972.

Boulier, J. F., J. Touma, and M. Vauclin, Flux concentration relation-based solution of constant flux infiltration equation: I. Infiltration into nonuniform initial moisture profiles, *Soil Sci. Soc. Am. J., 48,* 245–251, 1984.

Bouma, J., P. J. M. de Laat, A. F. van Holst, and T. J. von de Nes, Predicting the effects of changing water table levels and associated soil moisture regimes for soil survey interpretation, *Soil Sci. Soc. Am. J., 44,* 797–802, 1980.

Bresler, E., and G. Dagan, Solute dispersion in unsaturated heterogenous soil at field scale: II. Applications, *Soil Sci. Soc. Am. J., 43,* 467–472, 1979.

Bresler, E., and G. Dagan, Unsaturated flow in spatially variable fields: 2. Application of water flow models to various fields, *Water Resour. Res., 19,* 421–428, 1983.

Brigham, W. E., P. W. Reed, and J. N. Dew, Experiments on mixing during miscible displacement in porous media, *Soc. Petrol. Engrs. J., 1,* 1–8, 1961.

Broadbridge, P., and I. White, Constant rate rainfall infiltration: A versatile nonlinear model: 1. Analytic solution, *Water Resour. Res., 24,* 145–154, 1988.

Bromilow, R. H., and M. Leistra, Measured and simulated behavior of aldicarb and its oxidation products in fallow soils, *Pesticide Sci., 11,* 389–395, 1980.

Brooks, R. H., and A. T. Corey, Hydraulic properties of porous media, Hydrology Paper 3, Colorado St. Univ., Fort Collins, Colo., 1964.

Brutsaert, W., Probability laws for pore size distributions, *Soil Sci., 101,* 85–92, 1966.

Brutsaert, W., and H. Stricker, An advection-aridity approach to estimate actual regional evapotranspiration, *Water Resour. Res., 15,* 443–450, 1979.

Burdine, N. T., Relative permeability calculations from pore size distribution data, *Trans. Am. Inst. Univ. Metall. Pet. Eng., 198,* 71–87, 1953.

Cameron, D. A., and A. Klute, Convective-dispersive solute transport with a combined equilibrium and kinetic adsorption model, *Water Resour. Res., 13,* 183–188, 1977.

Carter, M. R. (Eds.), *Soil Sampling and Methods of Analysis*, Canadian Society of Soil Science, 823 pp., Lewis Publ., Boca Raton, FL, 1993.

Castro, C. L., and D. E. Rolston, Organic phosphate transport and hydrolysis in soil: Theoretical and experimental evaluation, *Soil Sci. Soc. Am. J., 41*, 1085–1092.

Chatzis, I., and F. A. L. Dullien, Modelling pore structure by 2-D and 3-D networks of capillary tubes to simulate the drainage capillary pressure of sandstones, *J. Can. Pet. Tech., 16,* 97–104, 1977.

Childs, E. C., and N. Collis-George, The permeability of porous materials, *Proceed. Royal Soc. London A., 210,* 392–405, 1950.

Cho, C. M., Convective transport of ammonium with nitrification in soil, *Can. J. Soil Sci., 51,* 339–350, 1971.

Chong, S. K., R. E. Green, and L. R. Ahuja, Simple *in situ* determination of hydraulic conductivity by power function descriptions of drainage, *Water Resour. Res., 17,* 1109–1114, 1981.

Chopart, J. L., and M. Vauclin. 1990. Water balance estimation model: Field test and sensitivity analysis, *Soil Sci. Soc. Am. J., 54,* 1377–1384, 1990.

Clausnitzer, V., J. W. Hopmans, and D. R. Nielsen, Simultaneous scaling of soil water retention and hydraulic conductivity curves, *Water Resour. Res., 28,* 19–31, 1992.

Clothier, B. E. and K. R. J. Smettem, Combining laboratory and field measurements to define the hydraulic properties of soil, *Soil Sci. Soc. Am. J., 54,* 299–304, 1990.

Clothier, B. E., and I. White, Measurement of sorptivity and soil water diffusivity in the field, *Soil Sci. Soc. Am. J., 45,* 241–245, 1981.

Coats, K. H., and B. D. Smith, Dead-end pore volume and dispersion in porous media, *Soc. Petrol. Engrs. J., 4,* 73–84, 1964.

Collis-George, N., and D. B. Yates, The first stage of drainage from ponded soils with encapsulated air, *Soil Sci., 149,* 103-111, 1990.

Conca, J. L., and J. V. Wright, Diffusion and flow in gravel, soil and whole rock, *Appl. Hydrogeol., 1,* 5-24, 1992.

Constanz, J., 1982. Temperature dependence of unsaturated hydraulic conductivity of two soils, *Soil Sci. Soc. Am. J., 46,* 466–470, 1982.

Cvetkovič, V. D., A continuum approach to high velocity flow in a porous medium, *Transp. Porous Media, 1,* 63–97, 1986.

Cvetkovič, V. D., Mass arrival of reactive solute in single fractures, *Water Resour. Res., 27,* 177–183, 1991.

Dagan, G., Statistical theory of groundwater flow and transport: Pore to laboratory, laboratory to formation and formation to regional scale, *Water Resour. Res., 22,* 102–135, 1986.

Dagan, G., and E. Bresler, Solute dispersion in unsaturated heterogenous soil at field scale: I. Theory, *Soil Sci. Soc. Am. J., 43,* 461–467, 1979.

Dagan, G., and E. Bresler, Unsaturated flow in spatially variable fields: 1. Derivation of models of infiltration and redistribution, *Water Resour. Res., 19,* 413–420, 1983.

Dahiya, I. S., K. S. Grewal, R. Anlauf, and J. Richter, Desalinization of a salt-affected soil in plots of various sizes under two modes of water application, *J. Agric. Sci., Camb.,'104,* 19–26, 1985.

Danckwerts, P. V., Continuous flow systems, *Chem. Eng. Sci., 2,* 1–13, 1953.

Dane, J. H., and A. Klute, Salt effects on the hydraulic properties of a swelling soil, *Soil Sci. Soc. Am. J., 41,* 1043–1049, 1977.

Darcy, H., *Les Fontaines Publique de la Ville de Dijon,* Dalmont, Paris, 1856.

Davidson, J. M., D. R. Nielsen, and J. W. Biggar, The dependency of soil water uptake and release upon the applied pressure increment, *Soil Sci. Soc. Am. Proceed., 30,* 298–304, 1966.

de Josselin de Jong, G., Longitudinal and transverse diffusion in granular deposits, *Trans. Am. Geophys. Union, 39,* 67–74, 1958.

Diaz, C. E., I. Chatzis, and F. A. L. Dullien, Simulation of capillary pressure curves using bond correlated site percolation on a simple cubic network, *Transp. Porous Media, 2,* 215–240, 1987.

Diment, G. A., K. K. Watson, and P. J. Blennerhassett, Stability analysis of water movement in unsaturated porous materials: I. Theoretical consideration, *Water Resour. Res., 18,* 1248–1254, 1982.

Duffy, C., P. J. Wierenga, and R. A. Kselik, Variations in infiltration rate based on soil survey information and field measurements, New Mexico State Univ., Agr. Experiment Station Bull. 680, 1981.

Dykhuizen, R. C., Transport of solutes through unsaturated fractured media, *Water Resour. Res., 21,* 1531–1539, 1987.

Elrick, D. E., Transient two-phase capillary flow in porous media, *Phys. Fluids, 4,* 572–575, 1961.

FAO/UNESCO, *Soil map of the world,* third draft, FAO–UN, 1985.

Garrat, J. R., Flux-profile relationships above tall vegetation, *Quart. J. Roy. Meteor. Soc., 104,* 199–211, 1978.

Gelhar, L. W., A. L. Gutjahr, and R. L. Naff, Stochastic analysis of macrodispersion in aquifers. *Water Resour. Res., 15,* 1387–1397, 1979.

Gerke, H. H., and M. T. van Genuchten, A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media, *Water Resour. Res., 29,* 305–319, 1993.

Germann, P. F., and K. Beven, Kinematic wave approximation to infiltration into soils with sorbing macropores, *Water Resour. Res., 21,* 990–996, 1985.

Gish, T. J., and J. L. Starr, Temporal variability of infiltration under field conditions, in *Advances of Infiltration,* ASAE Publ. 11–83, St. Joseph, Mich., pp. 122–131, 1983.

Gish, T. J., and A. Shirmohammadi (Eds.), Preferential Flow: Proceedings of the National Symposium, 16-17 December 1991, Chicago, Illinois, ASAE, St. Joseph, MI.

Greminger, P. J., Y. K. Sud, and D. R. Nielsen, Spatial variability of field measured soil-water characteristics, *Soil Sci. Soc. Am. J., 49,* 1075–1082, 1985.

Hatano, R., and H. W. G. Boolting, Using fractal dimensions of stained flow patterns in a clay soil to predict bypass flow, *J. Hydrol., 135,* 121–131, 1992.

Hatano, R., H. Nakamoto, T. Sakuma, and H. Okajima, Evapotranspiration in cracked clay field soil, *Soil Sci. Plant Nutr., 34,* 547–555, 1988.

Haverkamp, R., M. Vauclin, and G. Vachaud, Error analysis in estimating soil water content from neutron probe measurements: 1. Local standpoint, *Soil Sci., 137,* 78–90, 1984.

Hill, D. E., and J. Y. Parlange, Wetting front instability in layered soils, *Soil Sci. Soc. Am. Proceed., 36,* 697–702, 1972.

Hillel, D., and D. E. Elrick (Eds.), *Scaling in Soil Physics: Principles and Applications,* SSSA Spec. Publ. No. 25, SSSA, Madison, Wisc., 1990.

Hillel, D., and W. R. Gardner, Transient infiltration into crust-topped profiles, *Soil Sci., 109,* 69–76, 1970.

Hopmans, J. W., and J. H. Dane, Temperature dependence of soil hydraulic properties, *Soil Sci. Soc. Am. J., 50,* 4–19, 1986.

Hopmans, J. W., and J. N. M. Stricker, Stochastic analysis of soil water regime in a watershed, *J. Hydrol., 105,* 57–84, 1989.

Jackson, R. D., S. B. Idso, and R. J. Reginato, Calculation of evaporation rates during the transition from energy-limiting to soil-limiting phases using albedo data, *Water Resour. Res., 12,* 23–26, 1976.

Jackson, R. D., B. A. Kimball, R. J. Reginato, and F. S. Nakayarna, Diurnal soil water evaporation: Time-depth-flux patterns, *Soil Sci. Soc. Am. Proceed., 37,* 505–509, 1973.

Jackson, R. D., R. J. Reginato, B. A. Kimball, and F. S. Nakayama, Diurnal soil water evaporation: Comparison of measured and calculated soil-water fluxes, *Soil Sci. Soc. Am. Proc., 38,* 861–866, 1974.

Jackson, T. J., Measuring surface soil moisture using passive microwave remote sensing, *Hydrol. Proc., 7,* 139–152, 1993.

Jackson, T. J., D. M. Le Vine, A. J. Griffis, D. C. Goodrich, T. J. Schmugge, C. T. Swift, and P. E. O'Neill, Soil moisture and rainfall estimation over a semiarid environment with the ESTAR microwave radiometer, *IEEE Trans. Geosci. Remote Sens., 31,* 836–841, 1993.

Jalota, S. K., and S. S. Prihar, Bare-soil evaporation in relation to tillage, in *Advances in Soil Science, 12,* edited by B. A. Stewart, 187–216, Springer Verlag, New York, 1990.

Jones, A. J., and R. J. Wagenet, *In situ* estimation of hydraulic conductivity using simplified methods, *Water Resour. Res., 20,* 1620–1626, 1984.

Journel, A. G., and C. J. Huijbregts, *Mining Geostatistics,* Academic Press, New York, 1978.

Jury, W. A, Simulation of solute transport with a transfer function model, *Water Resour. Res., 18,* 363–368, 1982.

Jury, W. A, Spatial variability of soil properties, in *Vadose Zone Modeling of Organic Pollutants,* edited by S. C. Hern and S. M. Melancon, pp. 245-269, Lewis Publishers, Chelsea, Mich., 1989.

Jury, W. A., and G. Sposito, Field calibration and validation of solute transport models for the unsaturated zone, *Soil Sci. Soc. Am. J., 49,* 1331–1341, 1985.

Kachanoski, R. G., and E. de Jong, Scale dependence and the temporal persistence of spatial patterns of soil water stroage, *Water Resour. Res., 24,* 85–91, 1988.

Katul, G. G., and M. B. Parlange, A Penman-Brutsaert model for wet surface evaporation, *Water Resour. Res., 28,* 121–126, 1992.

Katul, G. G., O. Wendroth, M. B. Parlange, C. E. Puente, M. V. Folegatti, and D. R. Nielsen, Estimation of *in situ* hydraulic conductivity function from nonlinear filtering theory, *Water Resour. Res., 29,* 1063–1076, 1993.

Kemper, W. D., Water and ion movement in thin films as influenced by the electrostatic charge and diffuse layer of cations associated with clay mineral surfaces, *Soil Sci. Soc. Am. Proceed., 24,* 10–16 1960.

Klute, A. (Ed.), *Methods of Soil Analysis,* Part 1, Agronomy Monograph Series No. 9 (2nd ed), ASA and SSSA, Madison, Wisc., 1986.

Kool, J. B., and J. C. Parker, Analysis of the inverse problem for transient unsaturated flow, *Water Resour. Res., 24,* 817–830, 1988.

Kutílek, M., K. Zayani, R. Haverkamp, J. Y. Parlange, and G. Vachaud, Scaling of the Richards' equation under invariant flux boundary conditions, *Water Resour. Res., 27,* 2181–2185, 1991.

Lapidus, L., and N. R. Amundson, Mathematics of adsorption in beds: VI. The effect of longitudinal diffusion in ion exchange and chromatographic columns, *J. Phys. Chem., 56,* 984–988, 1952.

Libardi, P. L., K. Reichardt, C. Jose, M. Bazza, and D. R. Nielsen, An approximate method of estimating soil water diffusivity for different soil bulk densities, *Water Resour. Res., 18,* 177–181, 1980.

Luckner, L., M. T. van Genuchten, and D. R. Nielsen, A consistent set of parametric models for the two-phase flow of immiscible fluids in the subsurface, *Water Resour. Res., 25,* 2187–2193, 1989.

Luckner, L., and W. M. Schestakow, *Migration Processes in the Soil and Groundwater Zone,* Lewis Publishers, Chelsea, Mich., 1991.

Malicki, M. A., R. Plagge, M. Renger, and R. Walczak, Application of time domain reflectometry soil moisture microprobe for the determination of unsaturated soil water characteristics from undisturbed soil cores, *Irrig. Sci., 13,* 65–72, 1992.

Manabe, S., and T. Delworth, The temporal variability of soil wetness and its impact on climate, *Clim. Change, 16,* 185–192, 1990.

Mantoglou, A., and L. W. Gelhar, Stochastic modeling of large-scale transient unsaturated flow systems, *Water Resour. Res., 23,* 37–46, 1987a.

Mantoglou, A., and L. W. Gelhar, Effective hydraulic conductivities of transient unsaturated flow in stratified soils, *Water Resour. Res., 23,* 57–67, 1987b.

Marshall, T. J., A relation between permeability and size distribution of pores, *J. Soil Sci., 9,* 1–8, 1958.

Matheron, G., *Regionalized Variables and Their Estimation* (in French), Editions Masson, Paris, 1965.

Mausbach, M. J., and L. P. Wilding, *Spatial Variabilities of Soils and Landforms,* SSSA Spec. Publ. No. 28, Soil Sci. Soc. Am., Madison, Wisc., 1991.

McLaren, A. D., Temporal and vectorial reactions of nitrogen in soil: A review, *Can. J. Soil Sci., 50,* 97–109, 1970.

McNeal, B. L., Prediction of the effect of mixed-salt solutions on soil hydraulic conductivity, *Soil Sci. Soc. Am. Proceed., 32,* 190–193, 1968.

McNeal, B. L., D. A. Layfield, W. A. Norvell, and J. D. Rhoades, Factors influencing hydraulic conductivity of soils in the presence of mixed-salt solutions, *Soil Sci. Soc. Am. Proceed., 32,* 187–190, 1968.

Mein, R. G., and C. L. Larson, Modeling infiltration during a steady state rain, *Water Resour. Res. 9,* 384–394, 1973.

Miller, C. W., and L. V. Benson, Simulation of solute transport in a chemically reactive heterogeneous system: Model development and application, *Water Resour. Res.*, 19, 381–391, 1983.

Miller, E. E., and R. D. Miller, Physical theory for capillary flow phenomena, *J. Appl. Phys., 27,* 324-332, 1956.

Miller, R. J., J. W. Biggar, and D. R. Nielsen, Chloride displacement in Panoche clay loam in relation to water movement and distribution, *Water Resour. Res., 1,* 63–73, 1965.

Milly, P. C. D., A linear analysis of thermal effects on evaporation from soil, *Water Resour. Res., 20,* 1075–1086, 1984.

Milly, P. C. D., Integrated remote sensing modeling of soil moisture: sampling frequency, response time, and accuracy of estimates, *Proceed. Budapest Symp., Integrated Design of Hydrologic Network,* IAHS Publ. No. 158, pp. 201–211, 1986.

Milly, P. C. D., and Z. Kabala, Integrated modeling and remote sensing of soil moisture, *Proceed. Cocoa Beach Workshop, Hydrologic Applications of Space Technology,* IAHS Publ. No. 160, pp. 331–339, 1986.

Mishra, B. K., and C Misra, Nitrogen transformation during miscible displacement of ammonium nitrate solution through the root zone of maize, *J. Indian Soc. Soil Sci., 41,* 630–635, 1993.

Misra, C., D. R. Nielsen, and J. W. Biggar, Nitrogen transformations in soil during leaching: I. Theoretical considerations, *Soil Sci. Soc. Am. Proceed., 38,* 289–293, 1974.

Molz, F. J., Models of water transport in the soil-plant system: A review, *Water Resour. Res., 17,* 1245–1260, 1981.

Monin, A. S. and M. A. Obukhov, *Basic laws of turbulent mixing in the ground layer of the atmosphere*, Tr. Geofiz. Institut Akad. Nauk SSSR, pp. 163–187, 1954.

Morel-Seytoux, H. J., Analytical results for prediction of variable rainfall infiltration, *J. Hydrol., 59,* 209–230, 1982.

Morel-Seytoux, H. J., Infiltration affected by air, seal, crust, ice and various sources of heterogeneity, in *Advances in Infiltration,* ASAE Publ. 11-83, St. Joseph, Michigan, p. 132–146.

Mualem, Y., A new model for predicting the hydraulic conductivity of unsaturated porous media, *Water Resour. Res., 12,* 513–522, 1976.

Nielsen, D. R., J. W. Biggar, and K. T. Erh., Spatial variability of field measured soil water properties, *Hilgardia, 42,* 215–259, 1973.

Nielsen, D. R., M. T. van Genuchten, and J.W. Biggar, Water flow and solute transport processes in the unsaturated zone, *Water Resour. Res., 22,* 89S–108S, 1986.

Nimmo, J. R., J. Rubin, and D. P. Hammermeister, Unsaturated flow in a centrifugal field: measurement of hydraulic conductivity and testing of Darcy's law, *Water Resour. Res., 23,* 124–134, 1987.

Njoku, E. G., and J. A. Kong, Theory for passive microwave remote sensing of near-surface soil moisture, *J. Geophys. Res., 82,* 3108–3118, 1977.

Nkedi-Kizza, P., J. W. Biggar, M. T. van Genuchten, P. J. Wierenga, H. M. Selim, J. M. Davidson, and D.R. Nielsen, On the equivalence of two conceptual models for describing ion exchange during transport through an aggregated oxisol, *Water Resour. Res., 20,* 1123–1130, 1984.

Novák, V., Estimation of soil water extraction patterns by roots, *Agric. Water Mgt., 12,* 271–278, 1987.

Oatmans, H.D., Nonlinear theory for frontal stability and viscous fingering in porous media, *Soc. Petrol. Engr. J., 2,* 165–176, 1962.

Othmer, H., B. Diekkrüger, and M. Kutílek, Bimodal porosity and unsaturated hydraulic conductivity, *Soil Sci., 152,* 139–150, 1991.

Parlange, J. Y., and R. E. Smith, Ponding time for variable rainfall rates, *Can. J. Soil Sci., 56,* 212–223, 1976.

Parlange, J. Y., R. Haverkamp, and J. Touma, Infiltration under ponded conditions: I. Optimal analytical solution and comparison with experimental observations, *Soil Sci., 139,* 305–311, 1985.

Parlange, J. Y., I. Lisle, R. D. Braddock, and R. E. Smith, The three parameter infiltration equation, *Soil Sci., 133,* 337–341, 1982.

Parlange, M. B., and G. G. Katul, An advection-aridity evaporation model, *Water Resour. Res., 28,* 127–132, 1992.

Parlange, M. B., G. G. Katul, M. V. Folegatti, and D. R. Nielsen, Evaporation and the field scale soil water diffusivity function, *Water Resour. Res., 29,* 1279–1286, 1993.

Parlange, M. B., G. G. Katul, M. L. Kavvas, R. H. Cuenca, and D. R. Nielsen, Physical basis for a time series model of soil water content, *Water Resour. Res., 28,* 2437–2446, 1992.

Passerat de Silans, A., L. Bruckler, J. L. Thony, and M. Vauclin, Numerical modeling of coupled heat and water flows during drying in a stratified bare soil—Comparison with field obsersvations, *J. Hydrol., 105,* 109–138, 1989.

Penman, H. L., Natural evaporation from open water, bare soil and grass, *Proceed. Roy. Soc. London A., 193,* 120–145, 1948.

Pfannkuch, H. O., Contribution à l'étude des déplacements de fluides miscibles dans un milieu poreux, *Revue de l'Institut Francais du Pétrole, 18,* 215–270, 1962.

Philip, J. R., Theory of infiltration, *Advances Hydrosc., 5,* 215–305, 1969a.

Philip, J. R., and D. A. de Vries, Moisture movement in porous materials under temperature gradients, *Trans. Am. Geophys. Union, 38,* 222–232, 1957.

Priestly, C. H. B., and R. J. Taylor, On the assessment of surface heat flux and evaporation using large scale parameters, *Mon. Wea. Rev., 100,* 81–92, 1972.

Pullan, A., The quasilinear approximation for unsaturated porous media flow, *Water Resour. Res., 26,* 1219–1234, 1990.

Raats, P. A. C., On the roles of characteristic lengths and times in soil physical processes, in *Trans. 14th Intl. Congress of Soil Sci., I,* 202–207, ISSS, Kyoto, Japan, 1990.

Raupach, M. R., Canopy transport processes, in *Flow and Transport in the Natural Environment: Advances and Applications,* edited by W. L. Steffen and O. T. Denmead, pp. 95-127, Springer Verlag, Berlin, 1988.

Reardon, E. J., Kd's—Can they be used to describe reversible ion sorption reactions in contaminant migration?, *Ground Water, 19,* 279–286, 1981.

Reiniger, P., J. Hutson, H. Jansen, J. Kragt, H. Piehler, H. Swarts, and H. Vereecken, Evaluation and testing of models describing nitrogen transport and transformation in soil: A European project, *Trans. 14 Intl. Congress Soil Sci., I,* 156-161, ISSS, Kyoto, Japan, 1990.

Reynolds, W. D. and D. E. Elrick, In s*itu* measurement of field saturated hydraulic conductivity, sorptivity and the a-parameter using the Guelph permeameter, *Soil Sci., 140,* 292–301, 1985.

Richards, L. A., Capillary conduction of liquids through porous media, *Physics, 1,* 318–333, 1931.

Richter, O., P Nörtesheuser, and B. Diekkrüger, Modeling reactions and movement of organic chemicals in soils by coupling of biological and physical processes, *Modeling Geo-Biosphere Proceed., 1,* 95–114, 1992.

Rieu, M., and G. Sposito, Fractal fragmentation, soil porosity and soil water properties: I. Theory; II. Applications, *Soil Sci. Soc. Am. J., 55,* 1231–1238 and 1239–1244, 1991.

Ritchie, J.T., Model for predicting evaporation from a row crop with an incomplete cover, *Water Resour. Res., 8,* 1204–1212, 1972.

Rose, C. W., W. R. Stern, and J. E. Drummond, Determination of hydraulic conductivity as a function of depth and water content from a soil *in situ, Aust. J. Soil Res., 3,* 1–9, 1965.

Roth, K., and W. A. Jury, Modeling the transport of solutes to groundwater using transfer functions, *J. Environ. Qual., 22,* 487–493, 1993.

Russo, D., Stochastic modeling of macrodispersion for solute transport in a heterogeneous unsaturated porous formation, *Water Resour. Res., 29,* 383–397, 1993.

Russo, D., and E. Bresler, Field determinations of soil hydraulic properties for statistical analysis, *Soil Sci. Soc. Am. J., 44,* 682–687, 1980.

Russo, D., and E. Bresler, Effect of field variability in soil hydraulic properties on unsaturated water and salt flows, *Soil Sci. Soc. Am. J., 45,* 675–681, 1981.

Saffman, P. G., Dispersion due to molecular diffusion and macroscopic mixing in flow through a network of capillaries, *J. Fluid Mech., 7,* 194–208, 1960.

Sardin, M., D. Schweich, F. J. Leij, and M. T. van Genuchten, Modeling the nonequilibrium transport of linearly interacting solutes in porous media: A review, *Water Resour. Res., 27,* 2287–2307.

Shainberg, I., J. D. Rhoades and R. J. Prather, Effect of low electrolyte concentration on clay dispersion and hydraulic conductivity of a sodic soil, *Soil Sci. Soc. Am. J., 45,* 73–277, 1981.

Sharma, M. L., R. J. Luxmoore, R. de Angelis, R. C. Ward, and G. T. Yeh, Subsurface water flow simulated for hillslopes with spatially dependent soil hydraulic characteristics, *Water Resour. Res., 23,* 1523–1530, 1987.

Simmons. C. S., A stochastic-convective transport representation of dispersion in one-dimensional porous media systems, *Water Resour. Res., 18,* 1193–1214, 1982.

Simmons. C. S., D. R. Nielsen, and J. W. Biggar, Scaling of field-measured soil-water properties: I. Methodology; II. Hydraulic conductivity and flux, *Hilgardia, 47,* 74–173, 1979.

Ŝimůnek, J., and D. L. Suarez, *UNSATCHEM—2D Code for Simulating Two-Dimensional Variably Saturated Water Flow, Heat Transport, Carbon Dioxide Production and Transport and Multicomponent Solute Transport with Major Ion Equilibrium and Kinetic Chemistry,* Research Report No. 129, U.S. Salinity Laboratory, USDA, ARS, Riverside, Ca., 1993.

Ŝimůnek, J., and D. L. Suarez, Two-dimensional transport model for variably saturated porous media with major ion chemistry, *Water Resour. Res., 30,*1115–1133, 1994.

Skopp, J., Analysis of time-dependent chemical processes in soils, *J. Environ. Qual., 15,* 205–213, 1986.

Smith, R. E. and R. H. B. Hebbert, A Monte Carlo analysis of the hydrologic effects of spatial variability of infiltration, *Water Resour. Res., 15,* 419–429, 1979.

Soil Conservation Service, *Soil Taxonomy,* Agriculture Handbook No. 436, U.S. Dept. of Agriculture, Washington, D.C.

Sposito, G., and W. A. Jury, Miller similitude and generalized scaling analysis, in *Scaling in Soil Physics: Principles and Applications,* edited by D. Hillel and D. E. Elrick, pp. 13–22, SSSA Spec. Publ. No. 25, SSSA, Madison, Wisc., 1990.

Sposito, G., V. J. Gupta, and R. N. Bhattacharya, Foundation theories of solute transport in porous media: A critical review, *Advances in Water Res., 2,* 59–68, 1979.

Starr, J. L., F. E. Broadbent, and D. R. Nielsen, Nitrogen transformations during continuous leaching, *Soil Sci. Soc. Am. Proceed., 38,* 283–289, 1974.

Stein, A., I. G. Staritsky, J. Bouma, A. C. van Eijnsbergen, and A. K. Bregt, Simulation of moisture deficits and areal interpolation by universal cokriging, *Water Resour. Res., 27,* 1963–1973, 1991.

Sudicky, E. A., R. A. Gillham, and E.O. Frind, Experimental investigation of solute transport in stratified porous media: 1. The non-reactive case, *Water Resour. Res., 21,* 1035–1041, 1985.

Swartzendruber, D., A quasi-solution of Richards' equation for the downward infiltration of water into soil, *Water Resour. Res., 23,* 809–817, 1987.

Taylor, G. I., The instability of liquid surfaces when accelerated in a direction perpendicular to their planes, *Proceed. Roy. Soc. London A., 201,* 192–196, 1950.

Taylor, G. I., Dispersion of soluble matter in solvent flowing slowly through a tube, *Proceed. Roy. Soc. London A., 219,* 186–203, 1953.

Thom, A. S., Momentum, mass and heat exchange of plant communities, in *Vegetation and Atmosphere,* Vol. 1, edited by J.L. Monteith, pp. 57–109, Academic Press, London, 1975.

Thony, J. L., G. Vachaud, B. E. Clothier, and R. Angulo-Jaramillo, Field measurement of the hydraulic properties of soil, *Soil Tech., 4,* 111–123, 1991.

Topp. G. C., J. L. Davis, and A. P. Annan, Electromagnetic determination of soil water content: Measurements in coaxial transmission lines, *Water Resour. Res., 16,* 574–582, 1980.

Topp, G. C., W. D. Reynolds, and R. E. Green (Eds.), *Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice*, Special Publ. No. 30, 288 pp., Soil Science Society of America, Madison, WI, 1992.

Tyler, S. W., and S. W. Wheatcraft, Application of fractal mathematics to soil water retention estimation, *Soil Sci. Soc. Am. J., 53,* 987–996, 1989.

Uehara, G., B. B. Trangmar, and R. S. Yost, Spatial variability of soil parameters, in *Soil Spatial Variability,* edited by D. R. Nielsen and J. Bouma, pp. 61–95, Pudoc, Wageningen, The Netherlands, 1985.

Ulaby, F. T., and C. Elachi, *Radar Polarimetry for Geoscience Applications,* 364 pp., Artech House, Norwood, MA, 1990.

Vachaud, G., A. Passerat De Silane, P. Balabanis, and M. Vauclin, Temporal stability of spatially measured soil water probability density function, *Soil Sci. Soc. Am. J., 49,* 822–827, 1985.

Valocchi, A. J., Describing the transport of ion-exchanging contaminants using an effective K_d approach, *Water Resour. Res., 20,* 499–503, 1984.

van Genuchten, M. T., A closed form equation for predicting the hydraulic conductivity of unsaturated soils, *Soil Sci. Soc. Am. J., 44,* 892–898, 1980.

van Genuchten, M. T., and W. J. Alves, Analytic solutions of the one-dimensional convective-dispersive solute transport equation, Tech. Bull. 1661, U.S. Dept. of Agriculture, Washington, D.C., 1982.

van Genuchten, M. T., and D. R. Nielsen, On describing and predicting the hydraulic properties of unsaturated soils, *Annales Geophysicae, 3,* 615–628, 1985.

van Genuchten, M. T., and P. J. Wierenga, Mass transfer studies in sorbing porous media: I. Analytical solutions, *Soil Sci. Soc. Am. J., 40,* 473–480, 1976.

van Genuchten, M. T., J. M. Davidson, and P. J. Wierenga, An evaluation of kinetic and equiliibrium equations for the prediction of pesticide movement in porous media, *Soil Sci. Soc. Am. Proceed., 38,* 29–35, 1974.

van Genuchten, M. T., F. Kavel, W. B. Russell, and S. R. Yates, Direct and indirect methods for estimating the hydraulic properties of unsaturated soils, in *Land Qualities in Space and Time,* edited by J. Bouma and A. K. Bregt, p. 61–72, Pudoc, Wageningen, The Netherlands, 1989.

Vauclin, M., and G. Vachaud, Deterministic versus stochastic modelings of soil water balance components, *Trans. 14th Intl. Congress of Soil Sci., ISSS, Kyoto, I,* 16–19, 1990.

Vauclin, M., J. L. Thony, G. Vachaud, P. Revol, P. Ruelle, D. E. Elrick, and B. E. Clothier, Field determination of soil hydraulic properties by suction and pressure infiltrometers, paper presented at EGS XVI Meeting, Wiesbaden, Germany, April 1991.

Vogel, T., and M. Císlerová, On the reliability of unsaturated hydraulic conductivity calculated from the moisture retention curve, *Transp. Porous Media, 3,* 1–16, 1988.

Vogel, T., M. Císlerová, and J. W. Hopmans, Porous media with linearly variable hydraulic properties, *Water Resour. Res., 27,* 2735–2741, 1991.

Wagenet, R. J., J. W. Biggar, and D. R. Nielsen, Tracing the transformations of urea fertilizer during leaching, *Soil Sci. Soc. Am. J., 41,* 896–902, 1977.

Wang, J. R., P. E. O'Neill, T. J. Jackson, and E.,T. Engman, Multifrequency measurements of the effects of soil moisture, soil texture and surface roughness, *IEEE Geosci. Remote Sens.,* 21, 44–51, 1983.

Warrick, A. W., Application of scaling to the characterization of spatial variability in soils, in *Scaling in Soil Physics: Principles and Applications,* edited by D. Hillel and D.E. Elrick, pp. 39–57, SSSA Spec. Publ. No. 25, SSSA, Madison, Wisc., 1990.

Warrick, A. W., Inverse estimation of soil hydraulic properties with scaling: One dimensional infiltration, *Soil Sci. Soc. Am. J., 57,* 631–636, 1993.

Warrick, A. W., and A. A. Hussen, Scaling of Richards' equation for infiltration and drainage, *Soil Sci. Soc. Am. J., 57,* 15–18, 1993.

Warrick, A. W., D. O. Lomen, and A. Islas, An analytical solution to Richards' equation for a draining soil profile, *Water Resour. Res., 26,* 253–258, 1990.

Warrick, A. W., G. J. Mullen, and D. R. Nielsen, Scaling field properties using a similar media concept, *Water Resour. Res., 13,* 355–362, 1977.

Watson, K. K., An instantaneous profile method for determining the hydraulic conductivity of unsaturated porous materials, *Water Resour. Res., 2,* 709–715, 1966.

Webster, R., Automatic soil-boundary location from transect data, *Math. Geol., 5,* 27–37, 1973.

Webster, R., and M. A. Oliver, *Statistical Methods in Soil and Land Resource Survey,* Oxford Univ. Press, Oxford, England, 1990.

Wendroth, O., G. G. Katul, M. B. Parlange, C. E. Puente, and D. R. Nielsen, A nonlinear filtering approach for determining hydraulic conductivity functions, *Soil Sci., 156,* 293–301, 1993.

Wheatcraft, S. W., and J. H. Cushman, Hierarchical approaches to transport in heterogeneous porous media, *Rev. Geophys., 29,* Supplement, 261–267, 1991.

Whitaker, S., Flow in porous media: I. A theoretical derivation of Darcy's law, *Transp. Porous Media 1,* 3–25, 1986.

White, I., Measurement of soil physical properties in the field, in *Flow and Transport in the Natural Environment: Advances and Applications,* edited by W.L. Steffen and O.T. Denmead, Springer, Berlin, 1988.

White, I., and P. Broadbridge, Constant rate rainfall infiltration: A versatile nonlinear model: 2. Application of solutions, *Water Resour. Res., 24,* 155–162, 1988.

White, I., and K. M. Perroux, Use of sorptivity to determine field soil hydraulic properties, *Soil Sci. Soc. Am. J., 51,* 1093–1101, 1987.

White, I., and K. M. Perroux, Estimation of unsaturated hydraulic conductivity from field sorptivity measurements, *Soil Sci. Soc. Am. J., 53,* 324–329, 1989.

White, I., M. J. Sully, and M. D. Melville, Use and hydrological robustness of time-to-incipient ponding, *Soil Sci. Soc. Am. J., 53,* 1343–1346, 1989.

Wilding, L. P., Spatial variability: its documentation, accommodation and implication to soil surveys, in Soil Spatial Variability, edited by D.R. Nielsen and J. Bouma, Pudoc, Wageningen, The Netherllands, 1985.

Wopereis, M., M. Kropff, J. Bouma, A. van Wijk, and T. Woodhead, *Soil Physical Properties: Measurement and Use in Rice-Based Cropping Systems,* 111 pp., International Rice Research Institute, Laguna, Philippines, 1994.

Wösten, J. H. M., and M. T. van Genuchten, Using texture and other soil properties to predict the unsaturated soil hydraulic functions, *Soil Sci. Soc. Am. J., 52,* 1762–1770, 1988.

Wösten, J. H. M., J. Bouma, and G. H. Stoffelsen, Use of soil survey data for regional soil water simulation models, *Soil Sci. Soc. Am. J., 49,* 175–184, 1985.

Yang, S., Z. Lei, and Y Xue, An experimental study of local recharge in the thick unsaturated zone, *J. Hydraulic Eng., 1,* 495–502, 1992.

Yeh, G. T., and S. V. Tripathi, A model for simulating transport of reactive multispecies components: Model development and demonstration, *Water Resour. Res., 27,* 3075–3091, 1991.

Yeh, T. C., L. W. Gelhar, and A. L. Gutjahr, Stochastic analysis of unsaturated flow in heterogeneous soils: 1. Statistically anisotropic media with variable *a, Water Resour. Res., 21,* 447–456, 1985a.

Yeh, T. C., L. W. Gelhar, and A.L. Gutjahr, Stochastic analysis of unsaturated flow in heterogeneous soils: 2. Statistically isotropic media, *Water Resour. Res., 21,* 457–464, 1985b.

Yeh, T. C., L.W. Gelhar, and A. L. Gutjahr, Stochastic analysis of unsaturated flow in heterogeneous soils: 3. Observations and applications, *Water Resour. Res., 21,* 465–472, 1985c.

Youngs, E. G., An infiltration method of measuring the hydraulic conductivity of unsaturated porous materials, *Soil Sci., 97,* 307–311, 1964.

Youngs, E. G., The use of similar media theory in the consideration of soil water redistribution in infiltrated soils, in Advances in Infiltration, pp. 48–54, ASAE Publication 1183, St. Joseph, Mich., 1983.

Zaslavsky, D., and G. Sinai, Surface hydrology: IV. Flow in sloping layered soil, *ASCE 107*, No. HY 1, 1–93, 1981.

Ecology

Caldwell, M. M., and J. H. Richards, Competing root systems: Morphology and models of absorption, in *On the Economy of Plant Form and Function*, edited by T.J. Givnish, pp. 251–273, Cambridge Univ. Press, Cambridge, England, 1986.

Caldwell, M. M., and J. H. Richards, Hydraulic lift: Water efflux from upper roots improves effectiveness of water uptake by deep roots, *Oecologia, 79,* 1–5, 1989.

Davies, W. J., and J. Zhang, Root signals and the regulation of growth and development of plants in drying soil, *Annual Rev. Plant Physiol. Molecul. Biol., 42,* 55–76, 1991.

Davis, S. D., and H. A. Mooney, Comparative water relations of adjacent California shrub and grassland communities, *Oecologia, 66,* 522–529, 1985.

Davis, S. D., and H. A. Mooney, Water use patterns of four co-occuring chaparral shrubs, *Oecologia, 70,* 172–177, 1986.

Mooney, H. A., S. L. Gulmon, P. W. Rundel, and J. Ehleringer, Further observations on the water relations of *Prosopis tamarugo* of the northern Atacama desert, *Oecologia, 44,* 177–180, 1980.

Nemani, R., and S. W. Running, Estimating regional surface resistance to evapotranspiration from NDVI and thermal-IR AVHRR data, *J. Clim. Appl. Meteorol., 28,* 276–284, 1989.

Nepstad, D. C., C. R. de Carvalho, E. A. Davidson, P. H. Jipp, P. A. Lefebvre, G. H. Negreiros, E. D. da Silva, T. A. Stone, S. E. Trumbore, and S. Vieira, The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures, *Nature, 372,* 666–669, 1994.

Schulze, E. D., F. M. Kelliher, C. Körner, J. Lloyd, and R. Leuning, Relationship among maximum stomatal conductance, ecosystem surface conductance, carbon assimilation rate, and plant nitrogen nutrition: A global ecology scaling exercise, *Annual Rev. Ecol. Systemat., 25,* 629–660, 1994.

Schulze, E. D., Water and nutrient interactions with plant water stress, in *Responses of Plants to Multiple Stresses,* H. A. Mooney, W. E. Winner, and E. J. Pell, pp. 89–101, Academic Press, San Diego, 1991.

Meteorology

Abramopoulos, F., C. Rosenzweig, and B. Choudhury, Improved ground hydrology calculations for global climate models (GCM's): Soil water movement and evapotranspiration, *J. Climate, 1,* 921–941, 1988.

Arrett, R. W., and C. A. Clark, Functional relationship among soil moisture, vegetation cover and surface fluxes, *Proceed. AMS 21st Conference on Ag. and For. Meteorol.,* J37–J38, San Diego, CA, March 7–11, 1994.

Avissar, R., and R. A. Pielke, A parameterization of heterogeneous land surfaces for atmospheric numerical models and its impact on regional meteorology, *Mon. Wea. Rev., 117,* 2113–2136, 1989.

Capehart, W. J., and T. N. Carlson, Estimating near-surface soil moisture availability using a meteorologically driven soil water profile model, *J. Hydrol., 160,* 1–20, 1994.

Carlson, T. N., R. R. Gillies, and E. M. Perry, A method to make use of thermal infrared temperature and NDVI measurements to infer soil water content and fracitonal vegetation cover, *Remote Sens. Rev., 9,* 161–173, 1994.

Carlson, T. N., R. R. Gillies, and T. J. Schmugge, An interpretation of NDVI and radiant surface temperature as measures of surface soil water content and fractional vegetation cover, *Ag. For. Meteorol.,* 1995 (in press).

Carlson, T. N., O. Taconet, A. Vidal, R. R. Gillies, A. Olioso, and K. Humes, An overview of the workshop on thermal remote sensing held at La Londe les Maures, France, 20–23 September 1993, *Remote Sens. Rev. 12,* 147–158, 1995.

Chase, T.N., The sensitivity of a general circulation model to large scale vegetation changes, M.S. Thesis, Dept. of Atmospheric Science, Colorado State Univ., Ft. Collins, Fall 1994.

Copeland, J., Impact of soil moisture and vegetation distribution on climate as revealed by a regional climate model, Ph.D. Dissertation, Dept. of Atmospheric Science, Colorado State University, Ft. Collins, Fall 1994.

Diak, G. R., R. M. Rabin, K. P. Gallo, and C. M. Neale, Regional-scale comparisons of NDVI, soil moisture indices from surface and microwave data and surface energy budgets evaluated from satellite and in-situ data, *Remote Sens. Rev.,* 1995.

Friedel, M. A., and F. W. Davis, Sources of variation in radiometric surface temperature over a tall grass prairie, *Remote Sens. Environ., 48,* 1–17, 1994.

Gillies, R. R., and T. N. Carlson, Thermal remote sensing of surface soil water content with partial vegetation cover for incorporation into climate models, *J. Appl. Meteor. 34,* 745–756, 1995.

Mahfouf, J. F., Analysis of soil moisture from near surface parameters: A feasibility study, *J. Appl. Meteor., 30*, 1534–1547, 1991.

Mahfouf, J. F., and J. Noilhan, Comparative study of various formulations of evaporation from bare soil using in-situ data, *J. Appl. Meteor., 30,* 1354–1363, 1991.

Mihailovic, D. T., B. Rajkovic, L. Dekic, R. A. Pielke, T. J. Lee, and Z. Ye, The validation of various schemes for parameterizing evaporation from bare soil for use in meteorological models: A numerical study using in situ data, *Bound. Layer Meteor.,* 1995 (in press).

Nicholls, M. E., R. A. Pielke, J. L. Eastman, C. A. Finley, W. A. Lyons, C. J. Tremback, R. L. Walko, and W. R. Cotton, Applications of the RAMS numerical model to dispersion over urban areas, in *Wind Climate in Cities,* edited by J.E. Cermak, et al., pp. 703–732, Kluwer Academic Publishers, The Netherlands, 1995.

Ottle, C., and D. Vidal-Madjar, Assimilation of soil moisture inferred from infrared remote sensing in a hydrological model over the HAPEX-Mobilhy region, *J. Hydrol., 158,* 241–264, 1994.

Pielke, R. A., and X. Zeng, Influence on severe storm development of irrigated land, *Natl. Wea. Dig., 14,* 16–17, 1989.

Pielke, R. A., T. J. Lee, J. H. Copeland, J. L. Eastman, C. L. Ziegler, and C. A. Finley, Use of USGS-provided data to improve weather and climate simulations, *Ecol. Appl.,* 1995.

Price, J. C., Using spatial context in satellite data to infer regional scale evapotranspiration, *IEEE Trans. Geosci. Remote Sens., 28,* 940–948, 1990.

Smith, C. B., M. Lakhtakia, W. J. Capehart, and T. N. Carlson, Initialization of soil water content in regional-scale atmospheric prediction models, *Bull. Am. Meteor. Soc., 75,* 585–593, 1994.

Wetzel, P. J., D. Atlas, and R. H. Woodward, Determining soil moisture from geosynchronous satellite infrared data, *J. Climate and Appl. Meteor., 23*, 375-391, 1984.

Ye, Z., and R. A. Pielke, Atmospheric parameterization of evaporation from non-plant-covered surfaces, *J. Appl. Meteor., 32,* 1248–1258, 1993.

REPORT DOCUMENTATION PAGE

Form Approved No. 0704-0188

1. AGENCY USE ONLY *(leave blank)*	2. REPORT DATE November 1995	3. REPORT TYPE AND DATES COVERED Conference Publication

4. TITLE AND SUBTITLE

Soil Moisture: Report of a Workshop Held in Tiburon, California 25–27 January 1994

5. FUNDING NUMBERS

6. AUTHOR(S)

Ming-Ying Wei, Editor

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

NASA Headquarters

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, DC 20546

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
CP-3319

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified-Unlimited
Subject category - 42

12b. DISTRIBUTION CODE

13. ABSTRACT

A workshop on soil moisture was held to identify the scientific requirements of the atmospheric, hydrologic, and ecologic disciplines for soil moisture observations. These discussions are summarized and recommendations are made on promising avenues for research to further the knowledge of soil moisture, particularly the spatial and temporal evolution of the coupled moisture and temperature states. Appendices provide for the nonspecialist overviews of ground-based measurement techniques, microwave remote sensing, long-term soil moisture observations in the U.S. and Canada, soil water and solute transport equations, and a glossary of technical terms.

14. SUBJECT TERMS
soil moisture, moisture content, remote sensing, soil mapping, soil sampling, air-land interactions, hydrology, ecology

15. NUMBER OF PAGES 80

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	Unclassified

Available from NASA Center for AeroSpace Information
800 Elkridge Landing Road
Linthicum Heights, MD 21090-2934

National Aeronautics and
Space Administration
Mail Code YS
Washington, DC 20546-0001

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE $300